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Baughner

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(54) **REDUCED STIFFNESS
MICRO-MECHANICAL STRUCTURE**

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(2013.01)

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G01P 15/0802; G02B 7/182; G02B 6/3508;
G02B 6/35; G02B 6/3502; G02B 6/3506;
H01H 51/22; H01H 59/00
USPC 428/166; 251/129.01, 129.02, 129.06;
257/415; 200/600; 307/112; 337/333;
359/871; 385/16

See application file for complete search history.

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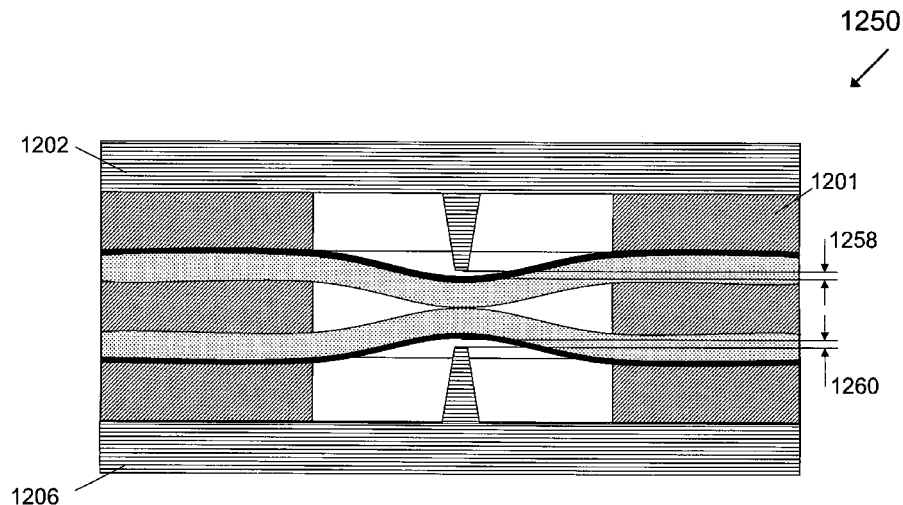
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(57) **ABSTRACT**

Apparatuses and method are described to create a reduced
stiffness microstructure (RSM). A RSM is made by forming
a first buckled membrane along a first buckling direction and
forming a second buckled membrane along a second buckling
direction. The second buckling direction is opposite to the
first buckling direction and the first buckled membrane is in
contact with the second buckled membrane over a contact
area. Within an operating zone, a stiffness of the reduced
stiffness microstructure spring is less than an absolute value
of a stiffness of either the first buckled membrane or the
second buckled membrane when the contact area translates
along either one of the buckling directions. In the operating
zone the stiffness can approach or equal zero.

17 Claims, 22 Drawing Sheets



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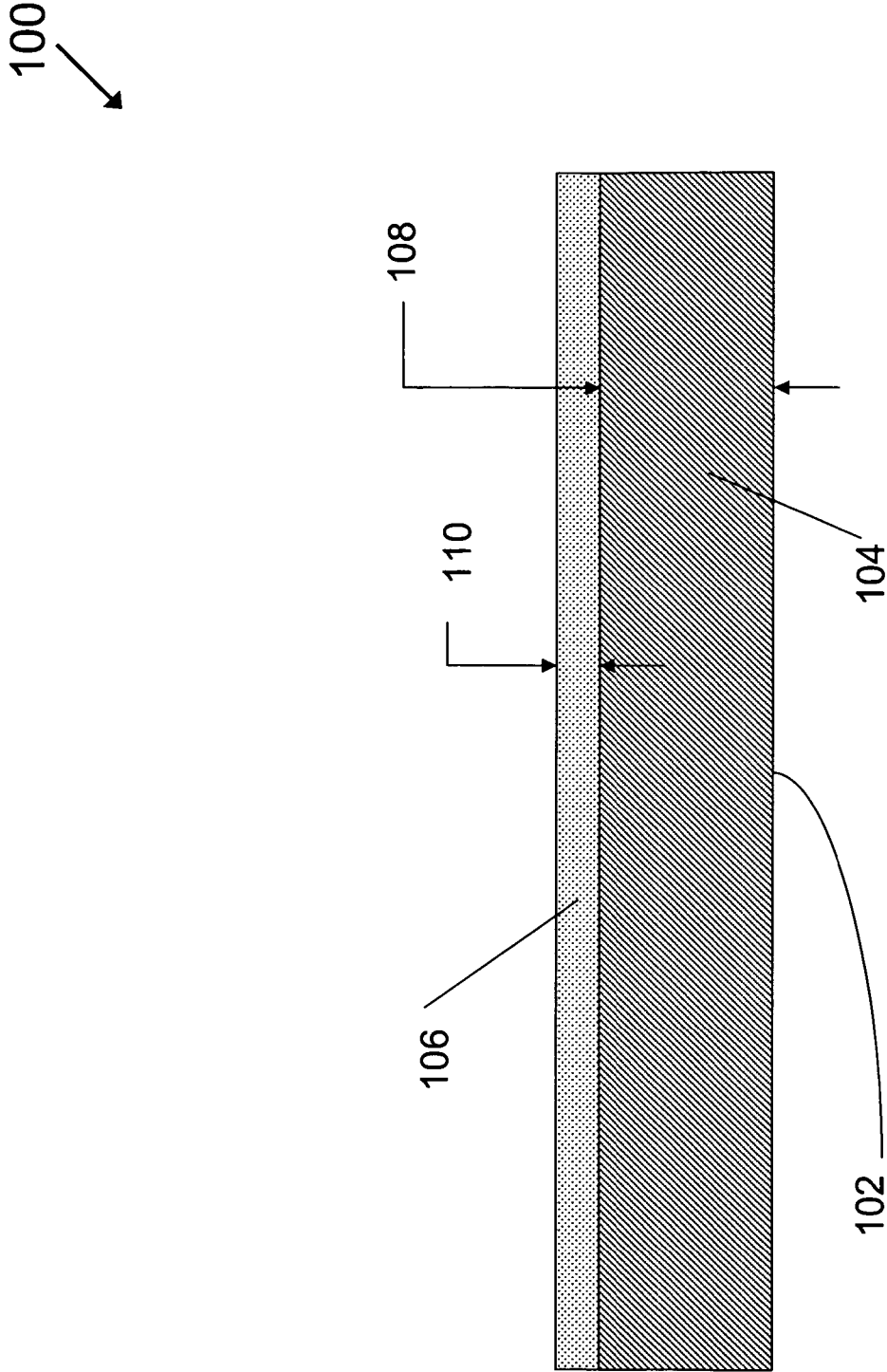
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FIG 1A



120

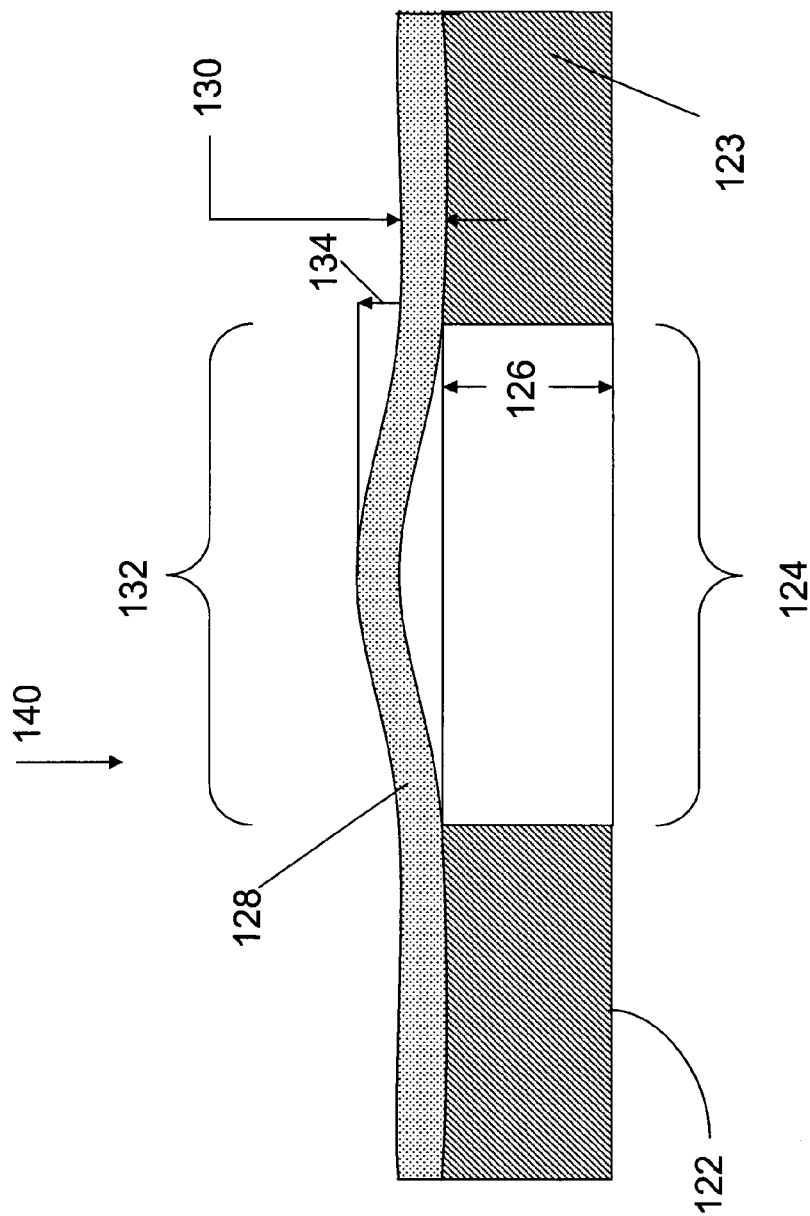


FIG 1B

140

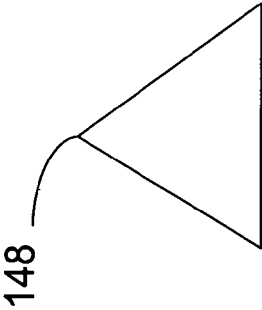
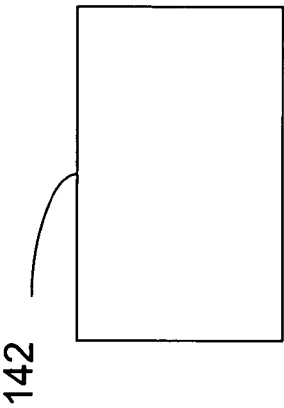
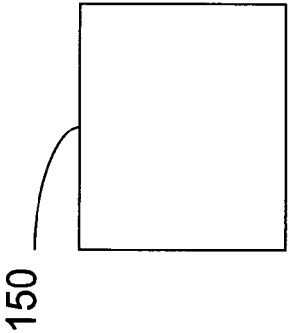
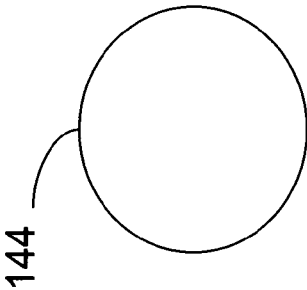
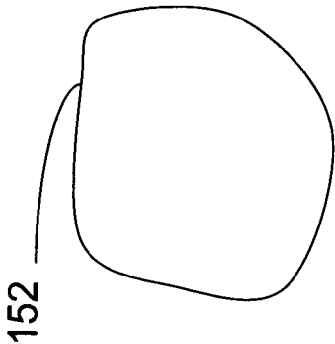
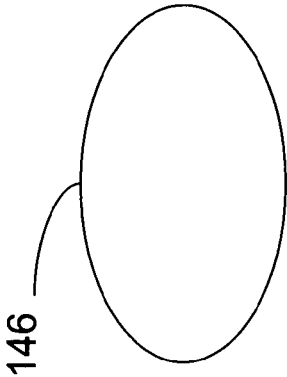


FIG 1C

FIG 2A

200

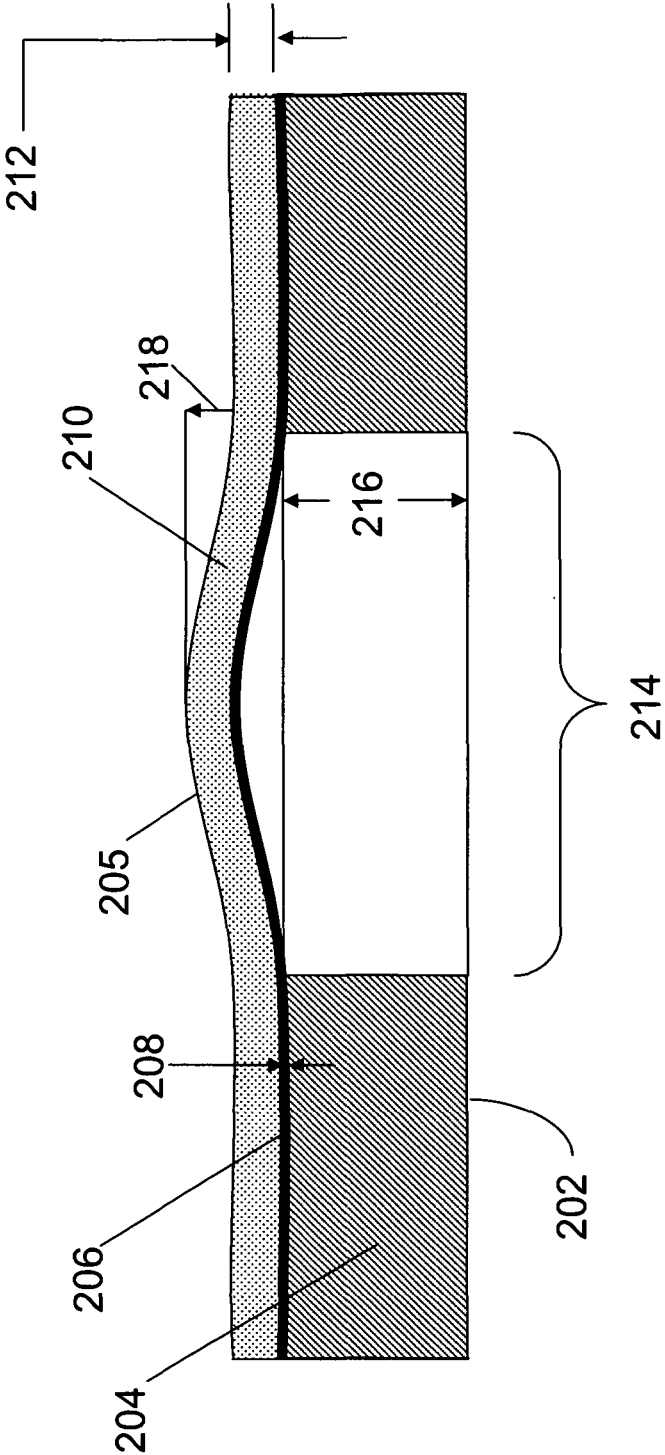


FIG 2B

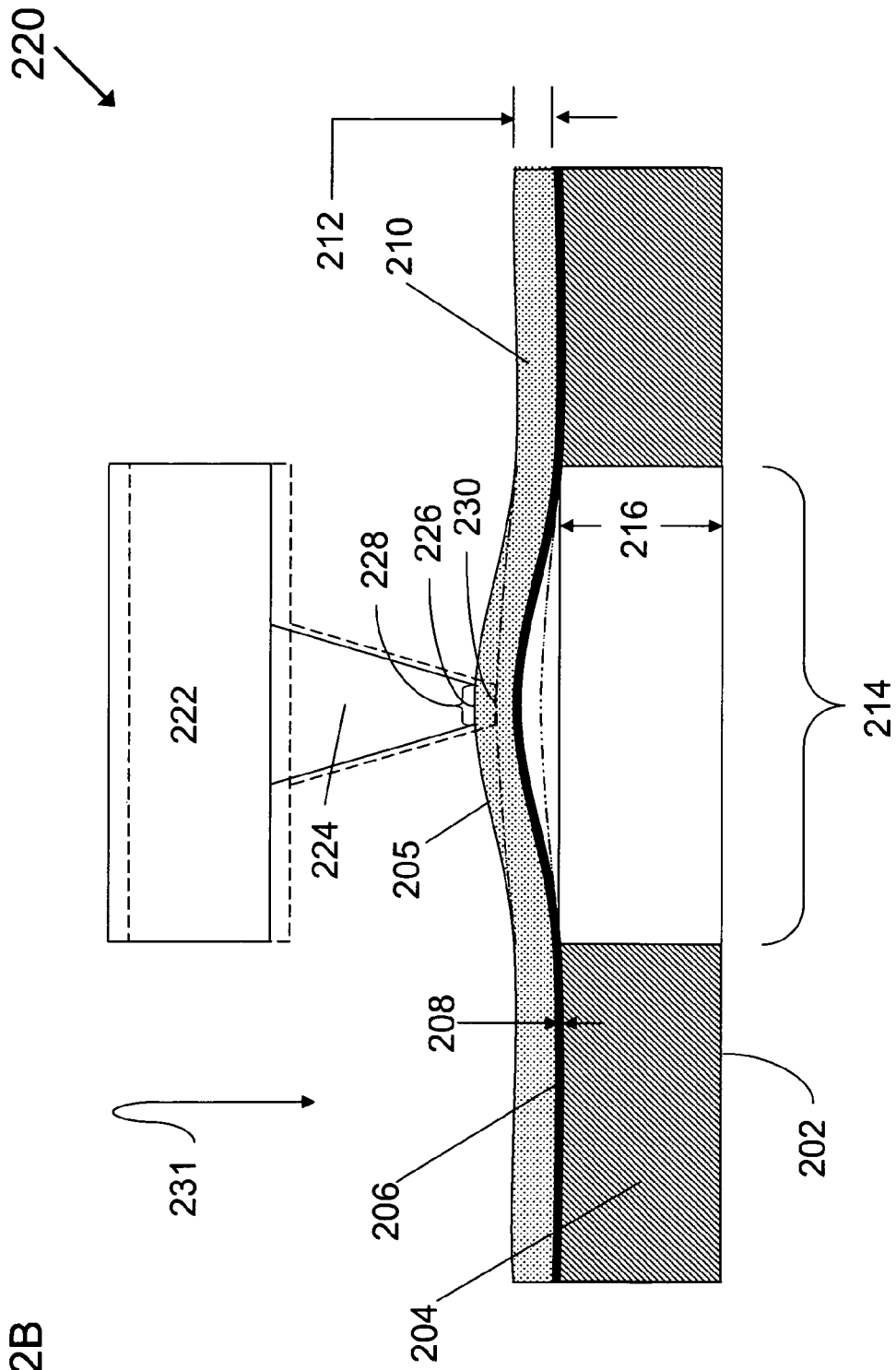
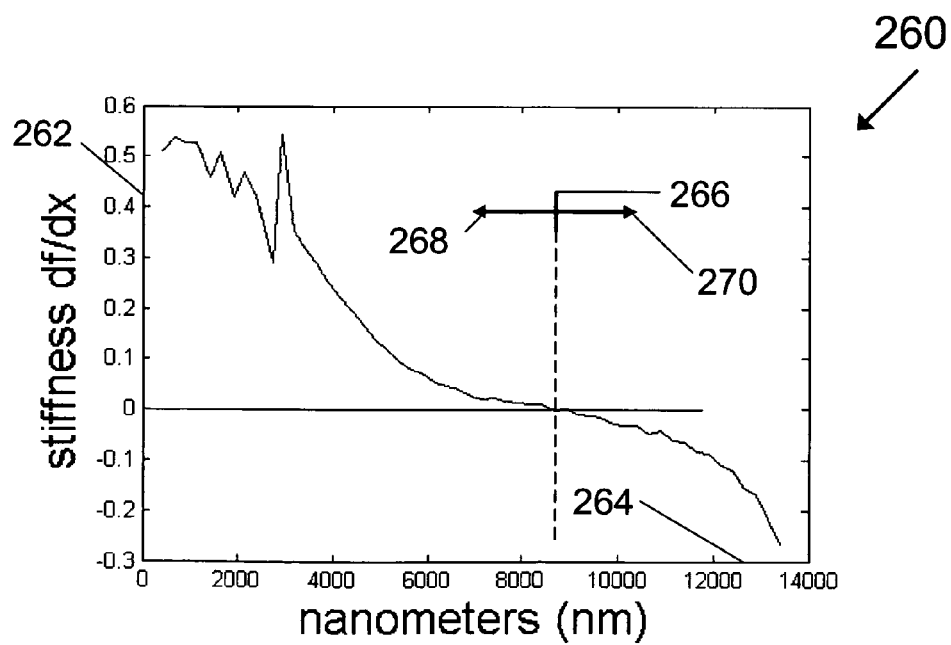
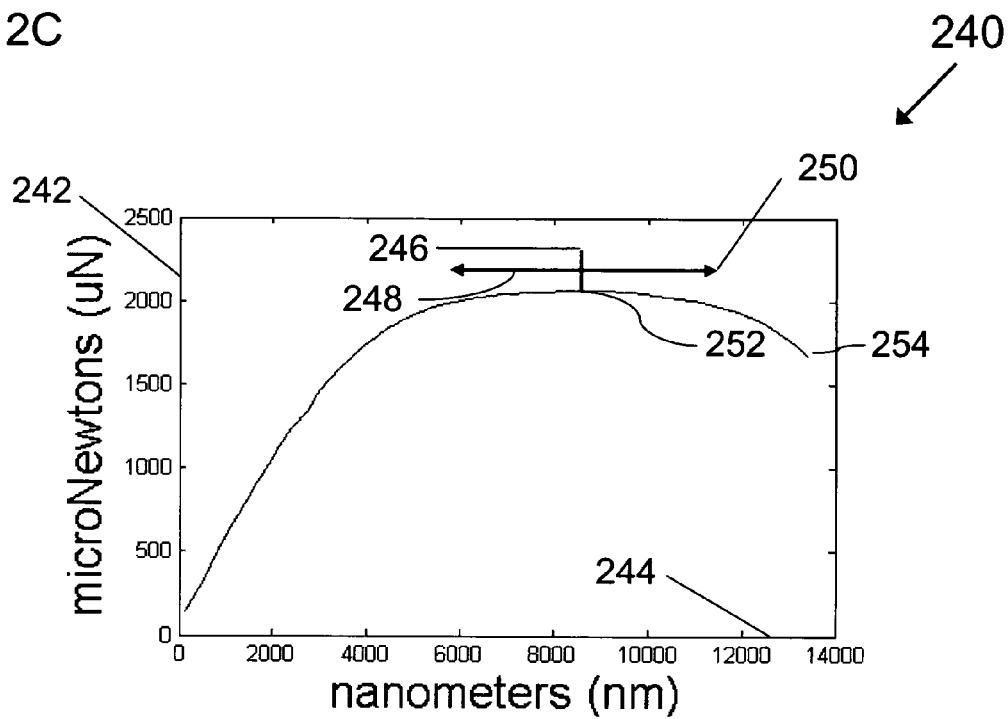
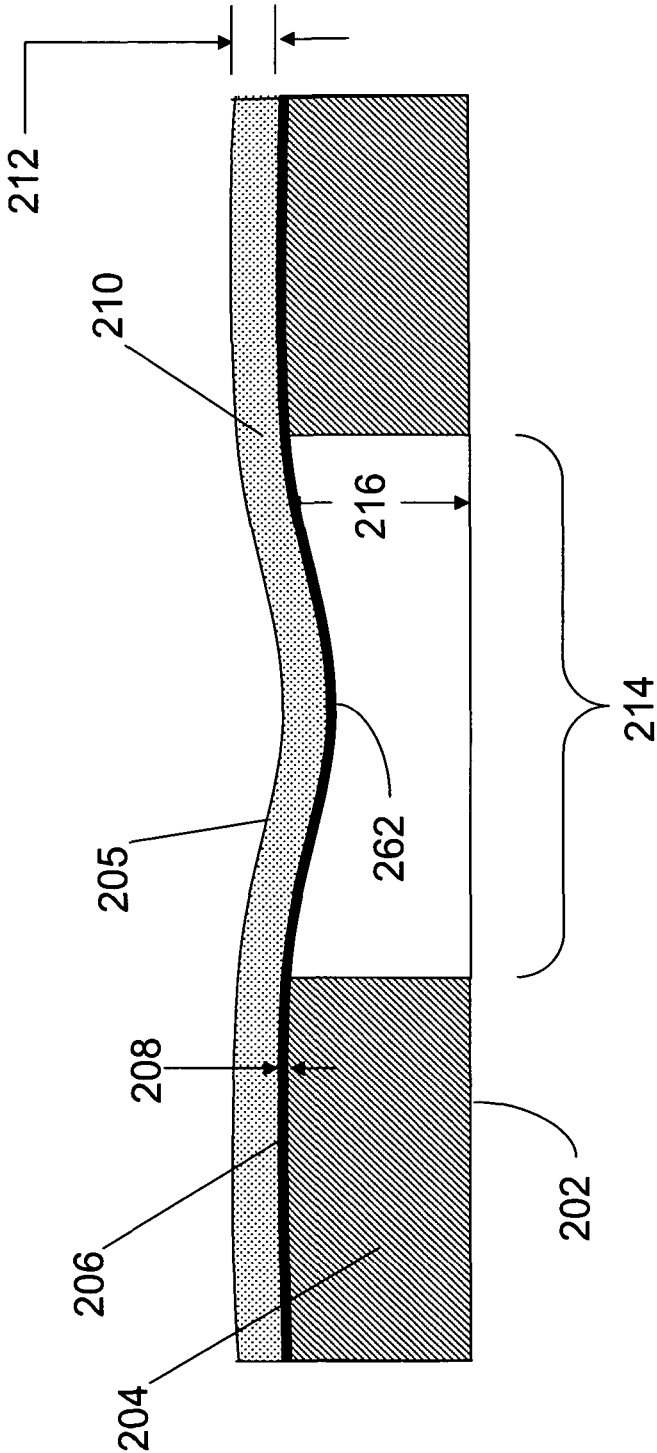


FIG 2C



260

FIG 2D



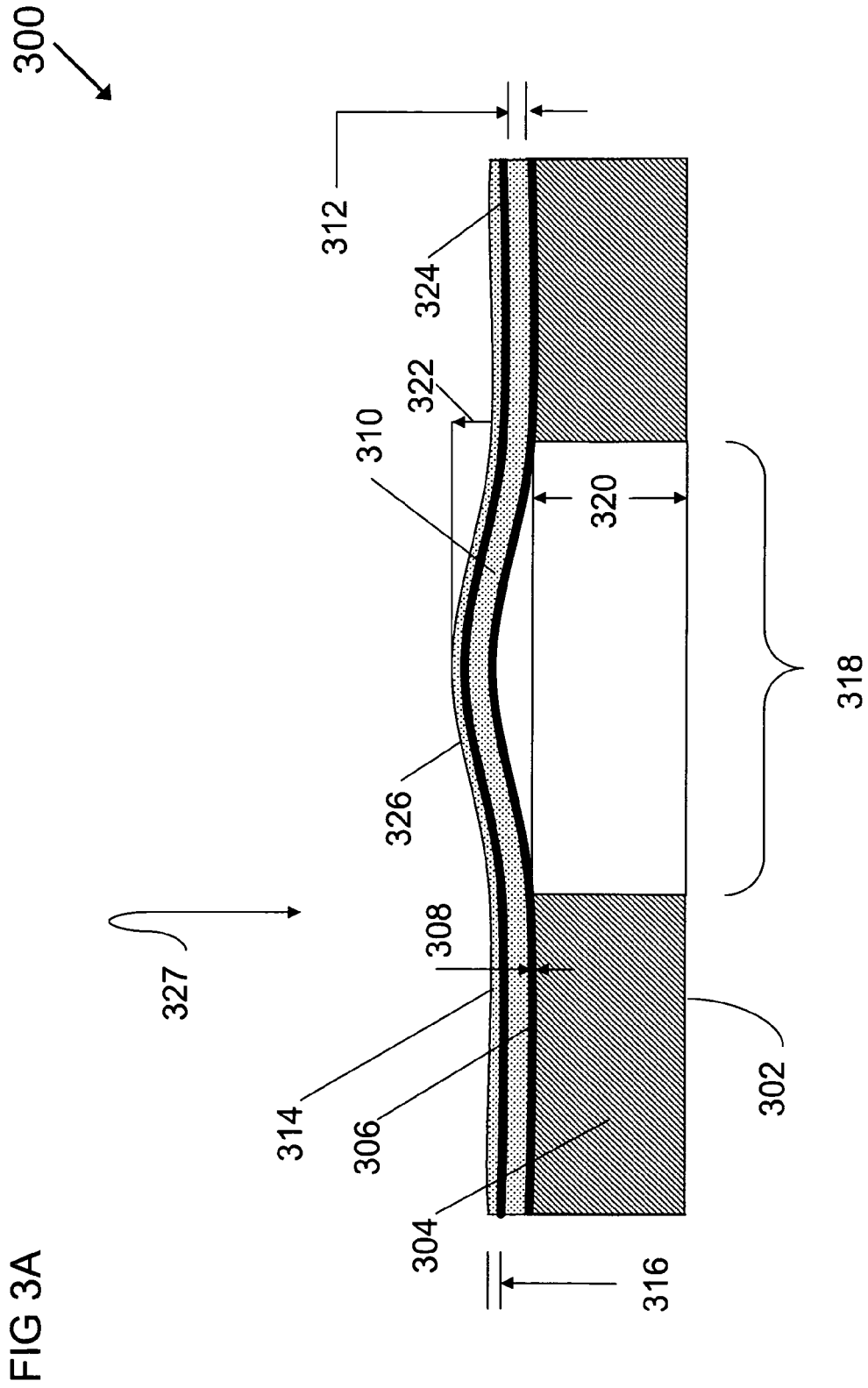


FIG 3B

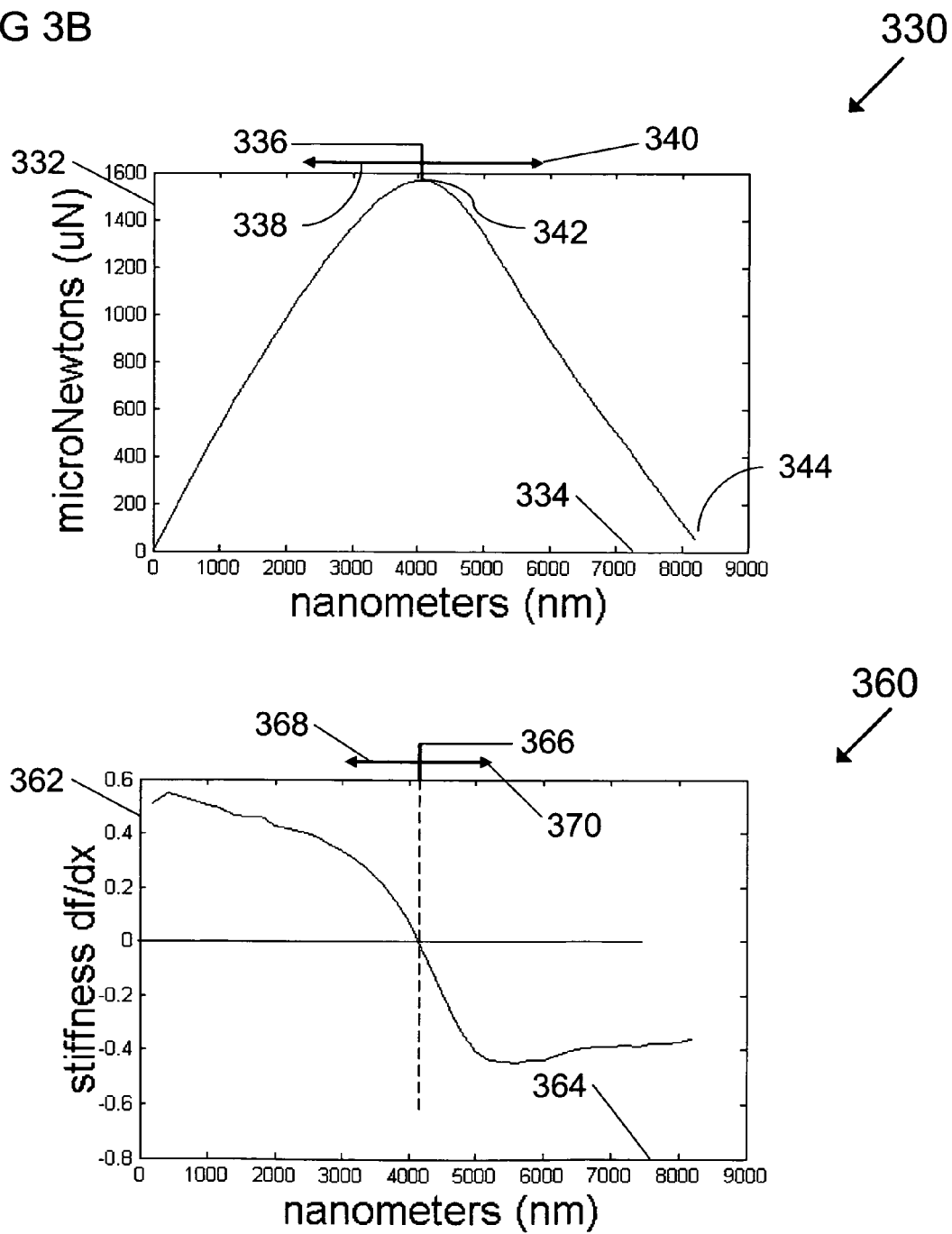
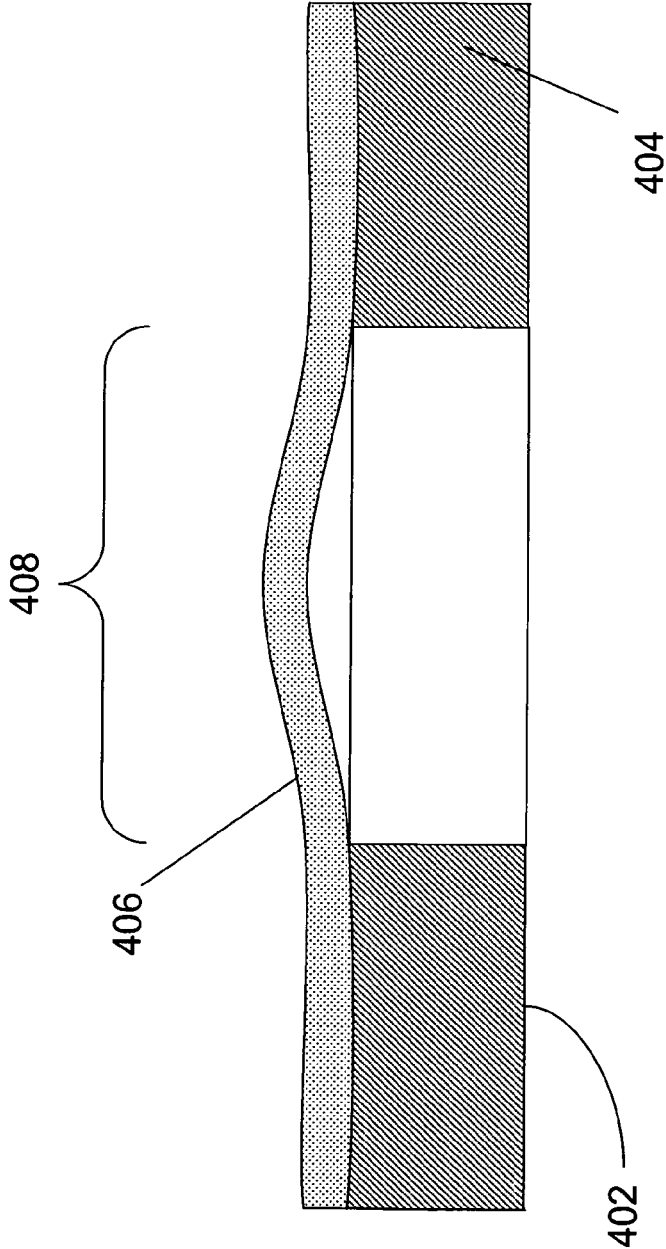
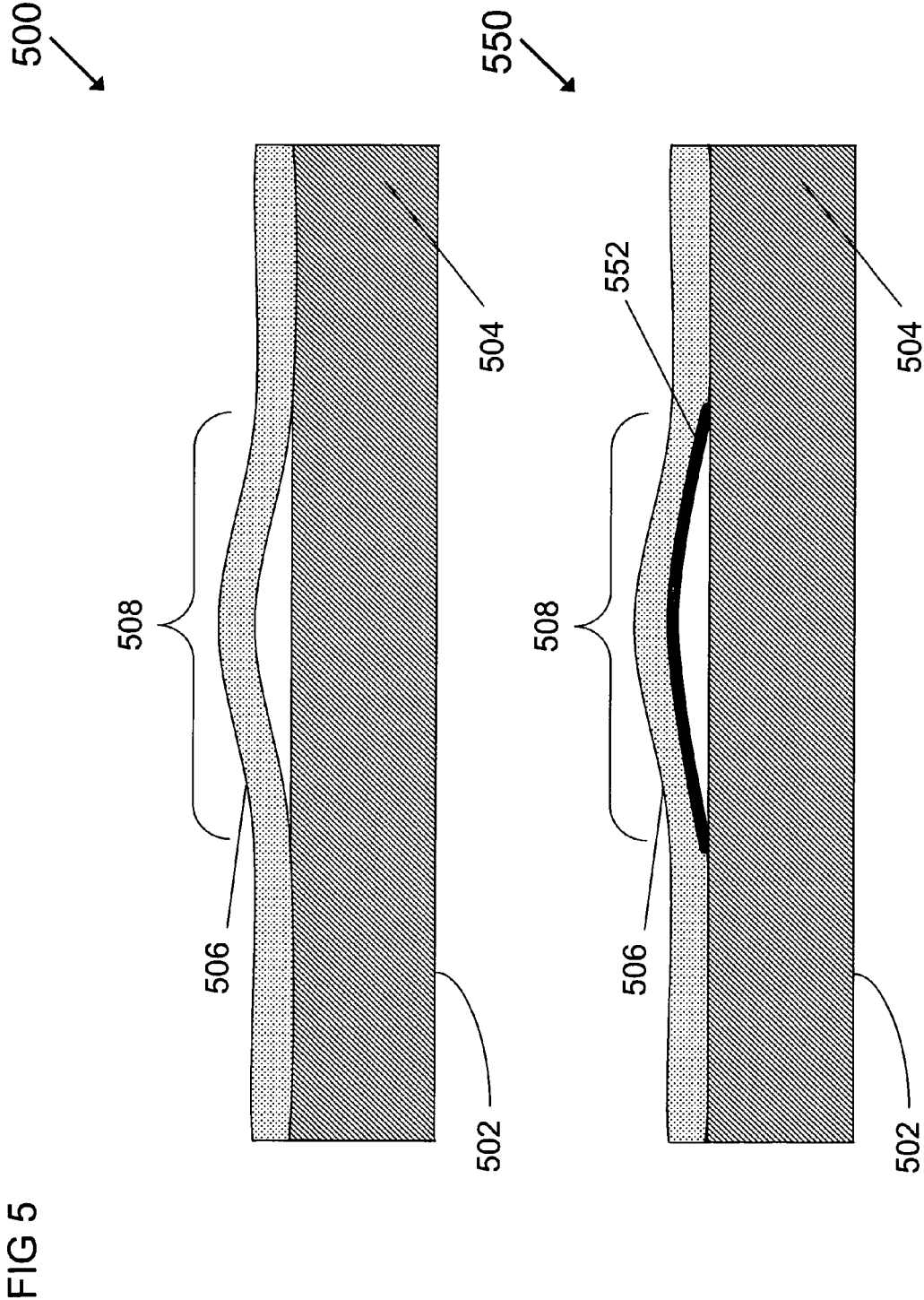
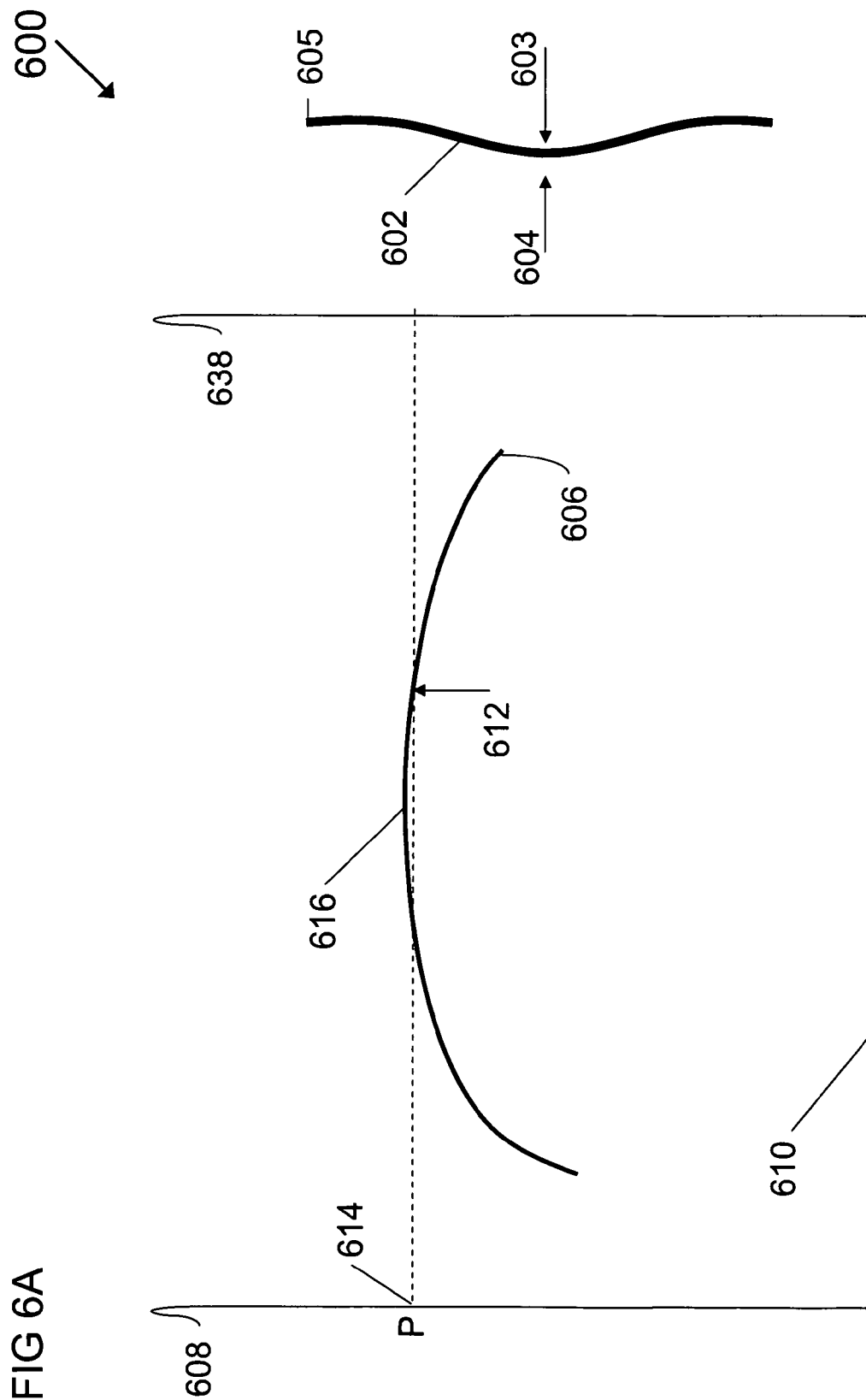


FIG 4

400







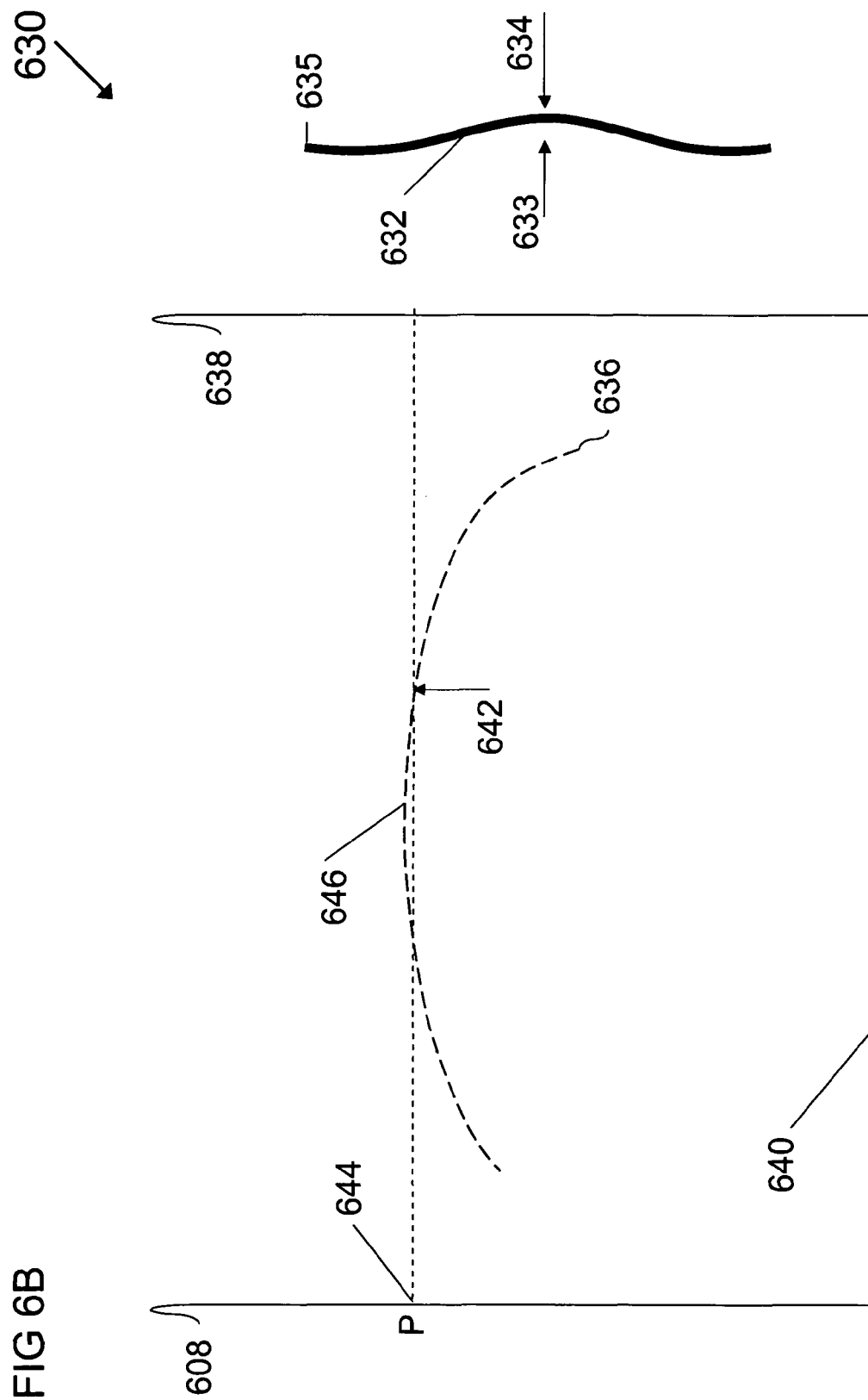
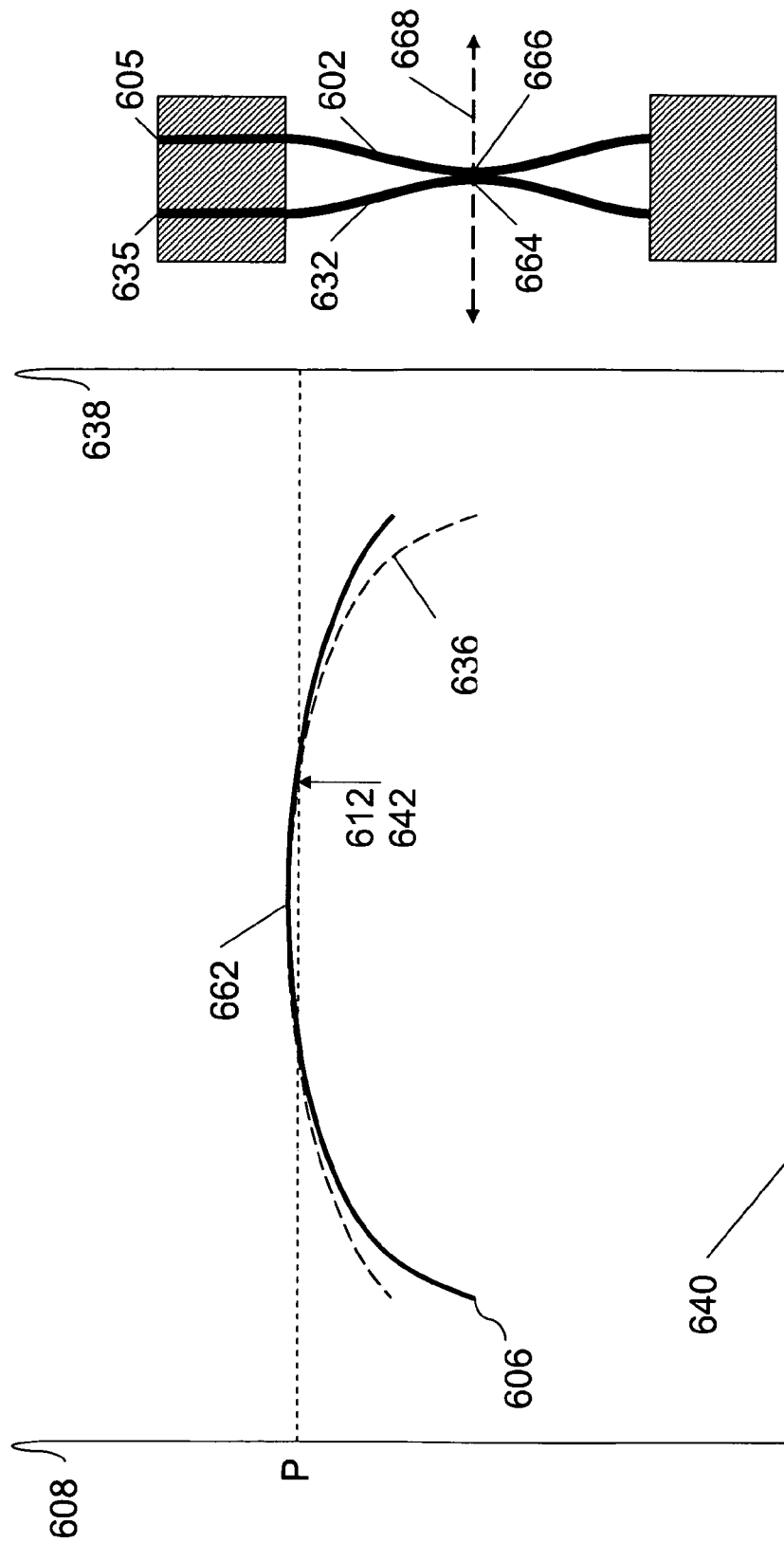
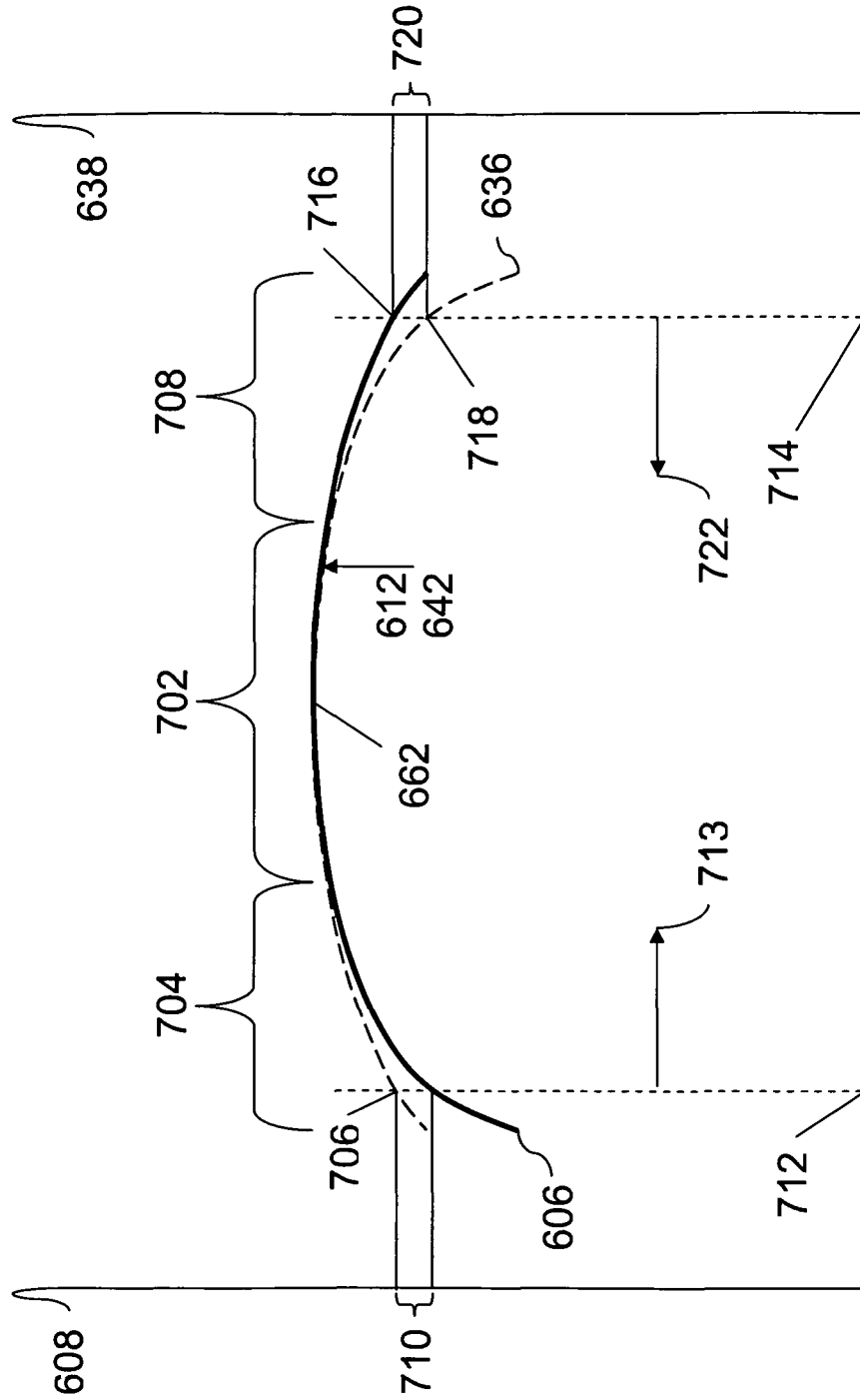


FIG 6C



660

FIG 7A



750

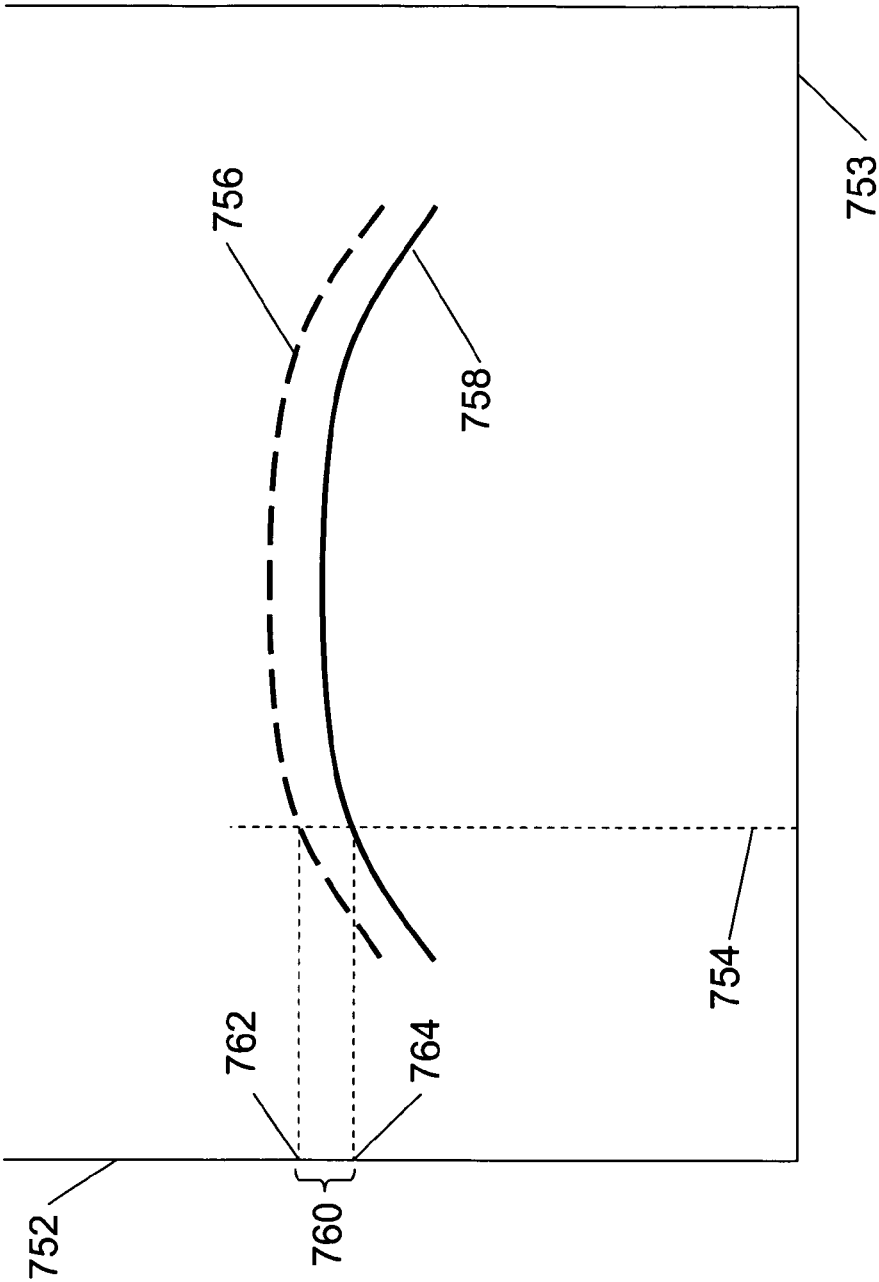
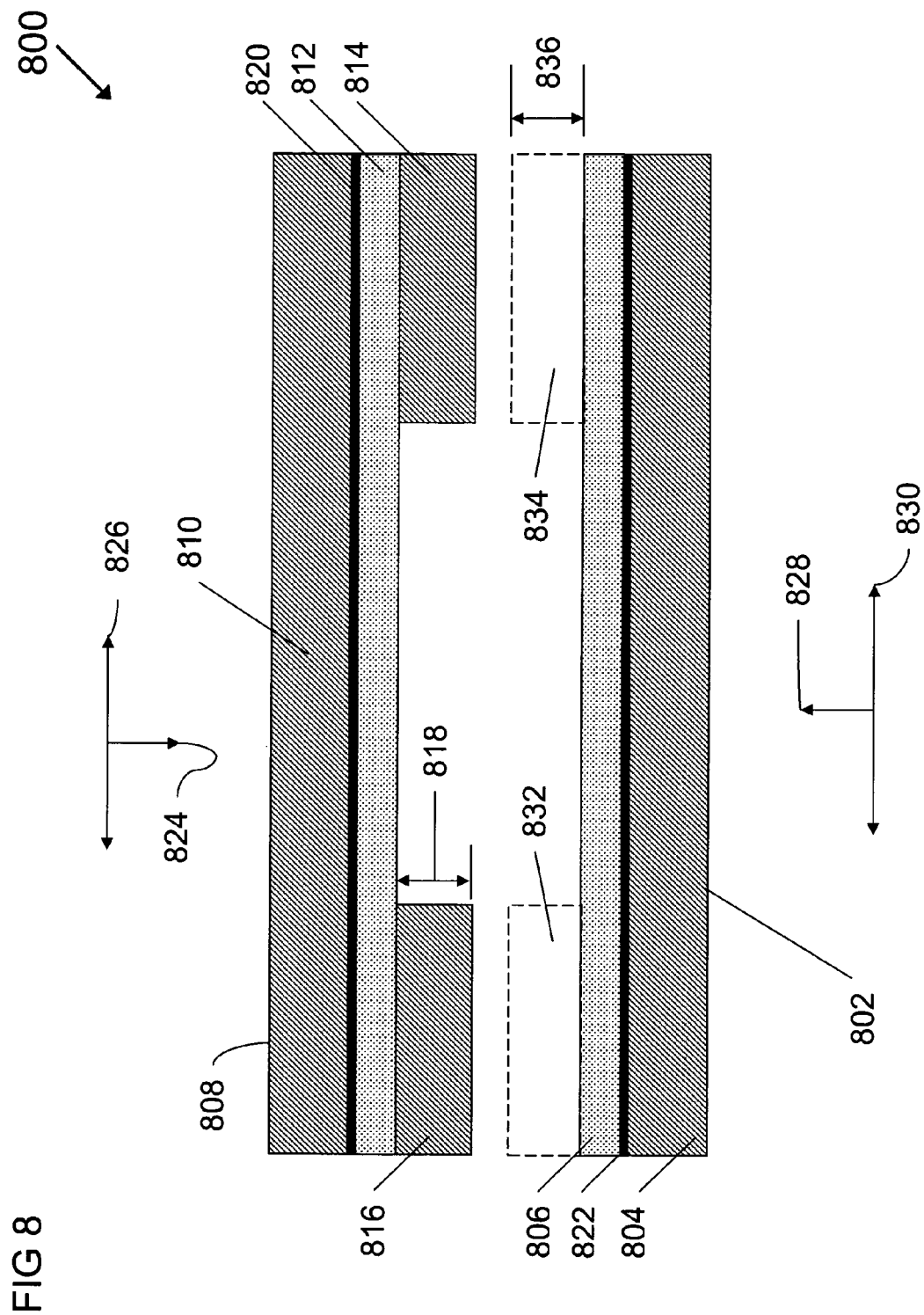
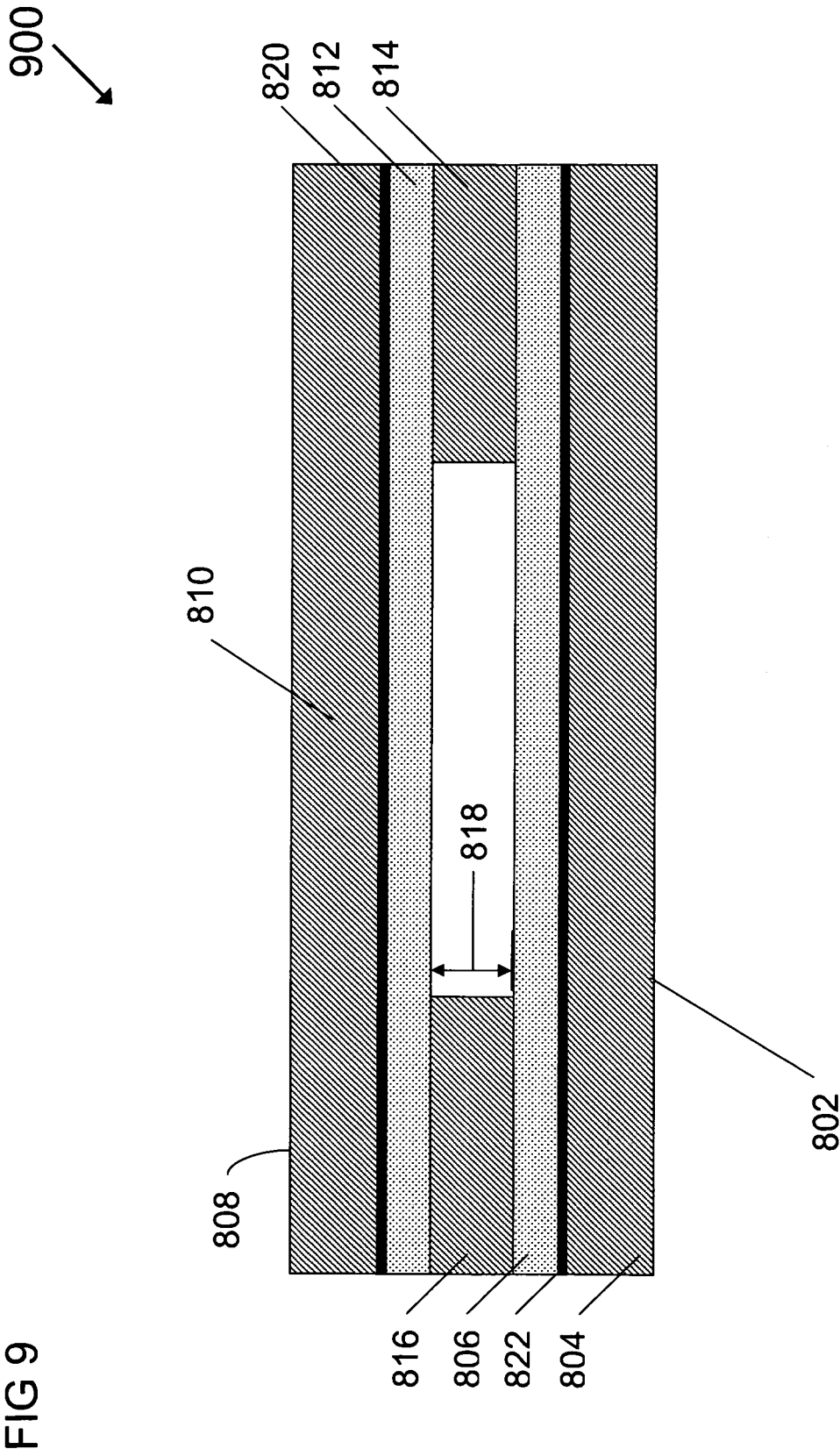


FIG 7B





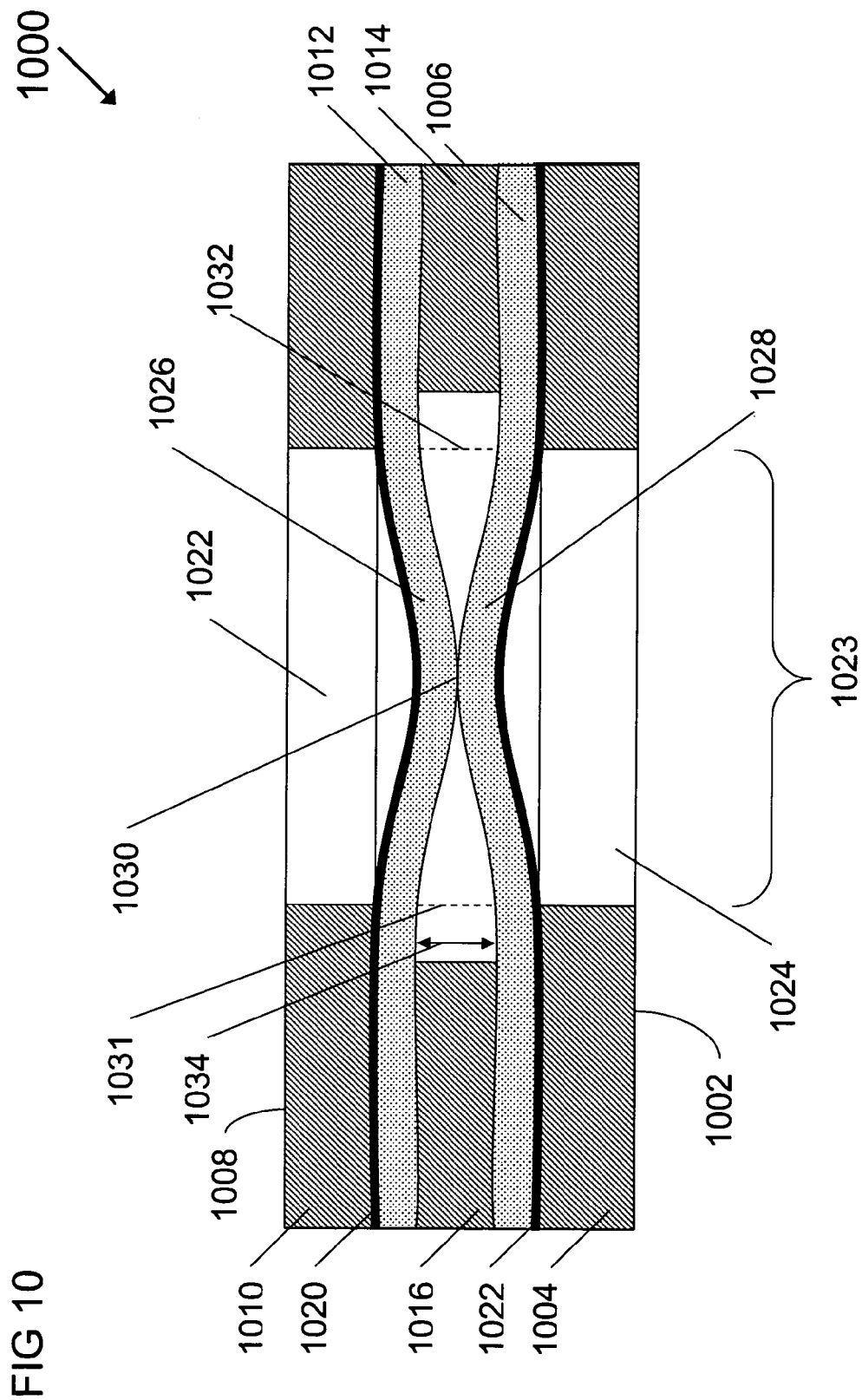
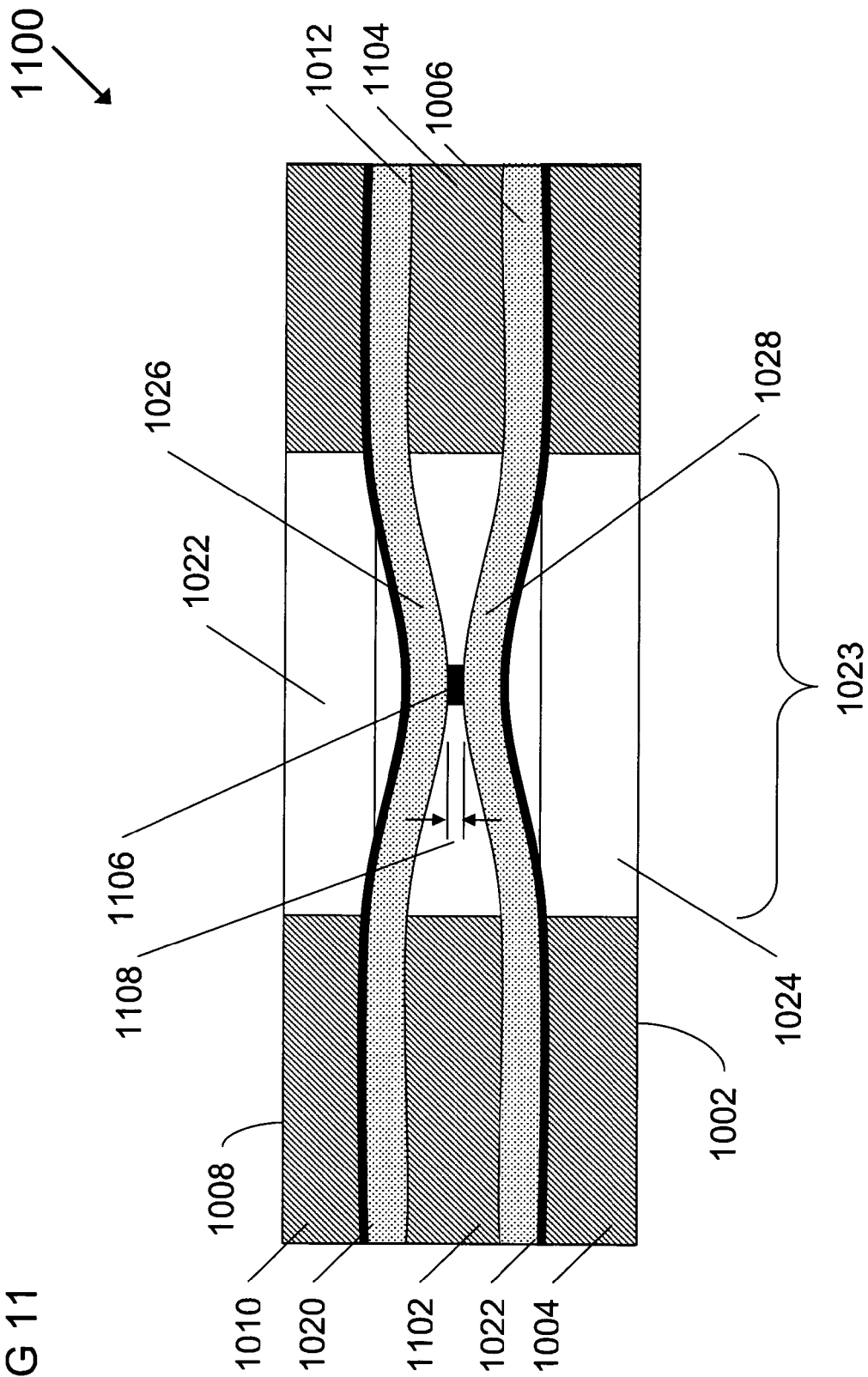
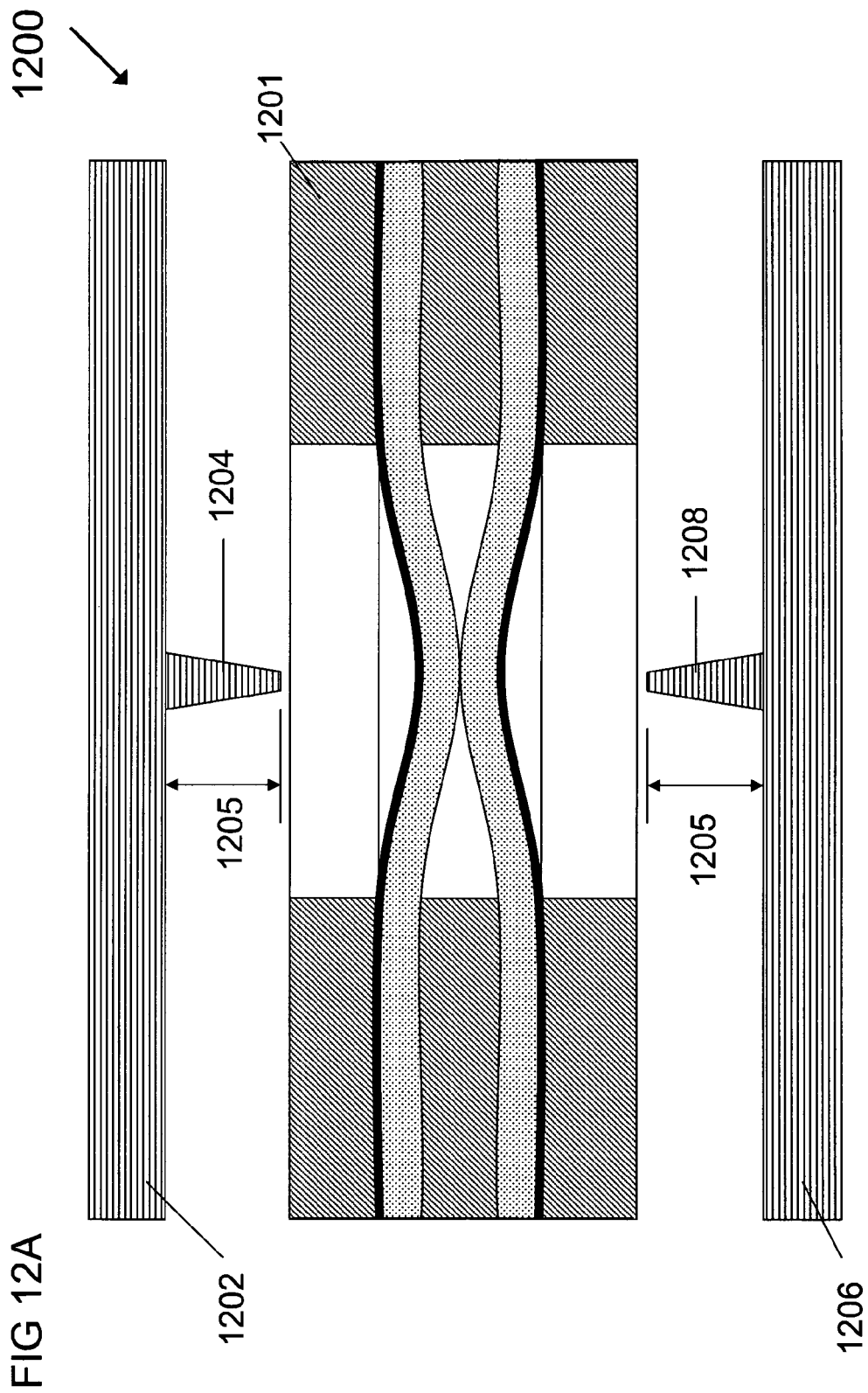


FIG 11





1250

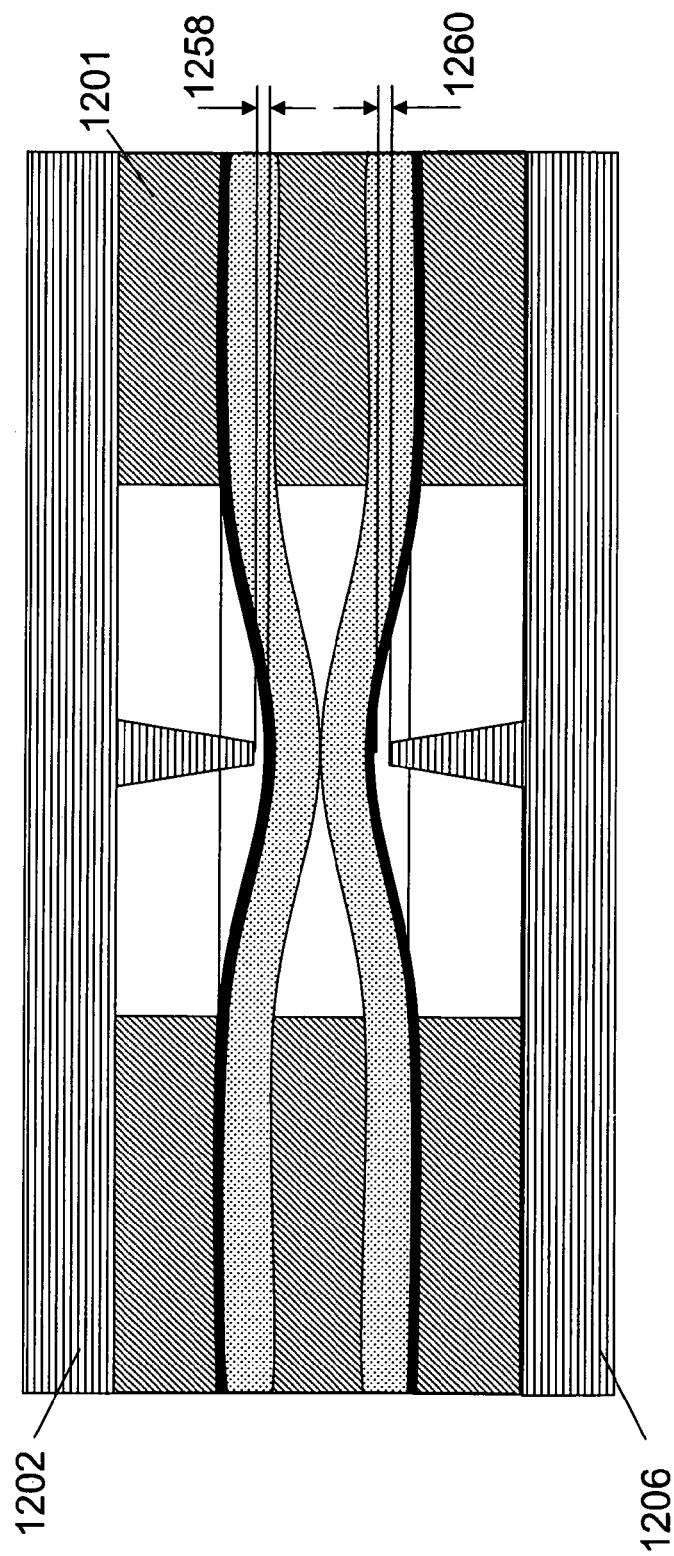


FIG 12B

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REDUCED STIFFNESS MICRO-MECHANICAL STRUCTURE

BACKGROUND OF THE INVENTION

1. Field of Invention

The invention relates generally to micro-electro-mechanical systems (MEMS) and or micro-opto-electro-mechanical systems (MOEMS), and more specifically to apparatuses and methods used to create a MEMS or MOEMS device that utilizes a zero stiffness or near zero stiffness elastic structure.

2. Art Background

Many devices made using MEMS and MOEMS routinely require elements to provide various functionalities, such as stiffness. MEMS and MOEMS elements that provide stiffness have traditionally been obtained from a device that has a positive spring constant or stiffness. Stiffness elements such as; straight beam suspensions, tether wires, meander springs, etc. are used to suspend elements used in MEMS and MOEMS devices. Such stiffness elements are characterized by positive stiffness. Designing elements for MEMS and MOEMS devices using only positive stiffness elements is limiting. All of this can present problems.

Capacitive MEMS switches are designed with a cantilever elastic element that is deflected when a voltage is applied. The large positive stiffness of such devices is required to overcome stiction from the physical stops once the actuation voltage is removed, and to ensure that no amount of signal noise could keep the switch closed. Actuation voltages on the order of tens of volts is often required, such levels place power demands on the power supply. This can present a problem.

Ohmic MEMS switches also rely on an elastic cantilever element in their design. Ohmic contacts tend to have an increase in stiction over the cycle lifetime of the switch due to plastic deformation of the contact surfaces. In order to develop a switch with a reasonable lifetime, a sufficiently high restoring force must be part of the design. The cantilever that the micro contact is mounted on must have an even greater stiffness than the capacitive MEMS switch, thus requiring an even larger actuation voltage. This can present a problem.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention may best be understood by referring to the following description and accompanying drawings that are used to illustrate embodiments of the invention. The invention is illustrated by way of example in the embodiments and is not limited in the figures of the accompanying drawings, in which like references indicate similar elements.

FIG. 1A illustrates a cross-sectional view of a multilayer microstructure, according to embodiments of the invention.

FIG. 1B illustrates a cross-sectional view of a buckled layer within a microstructure, according to embodiments of the invention.

FIG. 1C illustrates various projected areas of buckling layers within a microstructure, according to embodiments of the invention.

FIG. 2A illustrates a cross-sectional view of a multilayer buckling layer within a microstructure, according to embodiments of the invention.

FIG. 2B illustrates contacting a buckled microstructure membrane with a pseudo point load, according to embodiments of the invention.

FIG. 2C illustrates a force displacement curve for a multi-zone microstructure spring, according to embodiments of the invention.

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FIG. 2D illustrates a second stable state of a buckled membrane multi-zone microstructure spring, according to embodiments of the invention.

FIG. 3A illustrates a cross-sectional view of a buckled multi-layered membrane within a microstructure, according to embodiments of the invention.

FIG. 3B illustrates a force displacement curve for a multi-zone microstructure spring, according to additional embodiments of the invention.

FIG. 4 illustrates a cross-sectional view of a buckled layer within a microstructure, according to additional embodiments of the invention.

FIG. 5 illustrates a cross-sectional view of a buckled layer within a microstructure, according to additional embodiments of the invention.

FIG. 6A illustrates a force-displacement characteristic of a first buckled membrane, according to embodiments of the invention.

FIG. 6B illustrates a force-displacement characteristic of a second buckled membrane, according to embodiments of the invention.

FIG. 6C illustrates aligning load/displacement responses of two coupled buckled membranes to produce a reduced stiffness zone, according to embodiments of the invention.

FIG. 7A illustrates an operating zone of a reduced stiffness elastic micro-mechanical structure, according to embodiments of the invention.

FIG. 7B illustrates another operating zone of a reduced stiffness elastic micro-mechanical structure, according to embodiments of the invention.

FIG. 8 illustrates locating two substrates, according to embodiments of the invention.

FIG. 9 illustrates bonding two substrates together, according to embodiments of the invention.

FIG. 10, illustrates a pair of coupled buckled membranes, according to embodiments of the invention.

FIG. 11, illustrates a mass captured between a pair of coupled buckled membranes, according to embodiments of the invention.

FIG. 12A, illustrates stops used with a pair of coupled buckled membranes in an exploded view, according to embodiments of the invention.

FIG. 12B, illustrates stops used with a pair of coupled buckled membranes, according to embodiments of the invention.

DETAILED DESCRIPTION

In the following detailed description of embodiments of the invention, reference is made to the accompanying drawings in which like references indicate similar elements, and in which is shown by way of illustration, specific embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those of skill in the art to practice the invention. In other instances, well-known circuits, structures, and techniques have not been shown in detail in order not to obscure the understanding of this description. The following detailed description is, therefore, not to be taken in a limiting sense, and the scope of the invention is defined only by the appended claims.

Apparatuses and methods are described for creating a zero stiffness micro-mechanical structure. In one or more embodiments, a structure with zero stiffness or near zero stiffness is created from a pair of buckled membranes on a microstructure. In other embodiments a reduced stiffness micro-mechanical structure is created from a pair of buckled mem-

branes where the stiffness of the composite structure is a fraction of the stiffness of either individual buckled membrane.

In various embodiments, a reduced stiffness microstructure (RSM) is created from a pair of multi-zoned microstructure springs as described in this description of embodiments. As used in this description of embodiments, both zero-stiffness micro-mechanical structures and reduced stiffness micro-mechanical structures are included in the term RSM. The RSM can be used with micro-electro-mechanical systems (MEMS) devices and/or micro-opto-electro-mechanical systems (MOEMS) devices, or user defined devices that can incorporate aspects of both MEMS and MOEMS devices. Embodiments of the invention are not limited by the type of device used in conjunction therewith and those of skill in the art will recognize that a device can be user defined and embodiments of the invention can be used with devices that do not yet exist. Embodiments of the invention are not limited by the device used therewith. A non-limiting list of devices includes: gyroscopes, inertial sensors, gravitational sensors, accelerometers, seismic sensors, high-G sensors, pressure sensors, mirrors, tunable focal point mirrors, interferometric modulator displays, optical switches, optical cross connects, tunable lasers, switches, capacitive MEMS switches, ohmic MEMS switches, etc.

In all of the figures contained in this description of embodiments, geometrical elements are presented to illustrate concepts and parts of various microstructures. In so doing, geometrical elements such as: thickness, lengths, displacements, and shapes are shown which are not to scale. These geometrical elements have been chosen to facilitate understanding within the confines of the paper on which the illustrations are presented; therefore, relative proportions and absolute dimensions should not be inferred therefrom. Additionally, in the figures that follow, a finite horizontal extent of substrates and layers is shown such that only a single buckled membrane or a pair of opposing buckled membranes is illustrated in any given figure. Those of skill in the art will recognize that the substrates can extend horizontally to encompass many buckled membranes on a single substrate. No limitation is intended, and the finite extent of the substrate and buckled membranes is intended to preserve clarity in the illustrations.

FIG. 1A illustrates, generally at **100**, a cross-sectional view of a multilayered microstructure, according to embodiments of the invention. With reference to FIG. 1A, the multi-layered microstructure **102** has a substrate **104**, with a thickness indicated at **108**. The substrate **104** can be made from a semiconductor material such as silicon. A buckling layer is illustrated at **106**, with a thickness indicated at **110**. In the view shown in **100**, the buckling layer **106** has not released from the substrate **104**. The buckling layer **106** can be made of a variety of materials such as silicon dioxide, silicon nitride, etc. selected such that buckling is promoted in the final structure after processing.

In one or more embodiments, the buckling layer **106** can be made from a plurality of layers (sub-layers), as described below in the figures that follow, or the buckling layer can be a monolayer. An important property of the materials selected for the buckling layer and the substrate is that a compressive stress should be developed in the buckling layer relative to the substrate. This is accomplished by different methods in various embodiments, and in some embodiments it is accomplished by arranging for the coefficient of thermal expansion of the buckling layer to be less than the coefficient of thermal expansion of the substrate. Or in the case of a multilayered buckling layer, at least one layer of the sub-layers has a

coefficient of thermal expansion that is less than the coefficient of thermal expansion of the substrate.

The buckling layer and its sub-layers can be prepared from an inorganic material such as silicon, silicon dioxide in any of its forms (monocrystalline, polycrystalline, microcrystalline or amorphous) silicon germanium, silicon nitride, silicon carbide, diamond, carbon, titanium nitride, a metallic material such as for example, titanium, gold, copper, aluminum, or alloys thereof, an organic material such as for example, a photosensitive resin such as benzocyclobutene (BCB), parylene, polydimethylsiloxane (PDMS), polyethylene terephthalate (PET), poly-para-xylylene, etc. The buckling layer can be made by any known means or by yet unknown means, the exact way in which the buckling layer is made does not limit embodiments of the invention.

Some non-limiting examples of how a buckling layer can be formed by means known to those of skill in the art are, but are not limited to; thin film deposition, film lamination, spin definition, spraying organic materials, ion implantation, etc. Thin film deposition can be performed by chemical vapor deposition (CVD), low pressure chemical vapor deposition (LPCVD), plasma enhanced chemical vapor deposition (PECVD), physical vapor deposition (PVD), electrolysis, epitaxy, thermal oxidation, and vacuum deposition.

FIG. 1B illustrates, generally at **120**, a cross-sectional view of a buckled layer within a microstructure, according to embodiments of the invention. With reference to FIG. 1B, a microstructure **122** has a substrate **123** and a buckling layer **128**. A region having a width indicated by **124** is patterned and etched to a depth shown as **126**. Removal of substrate **123**, from the region **124**, causes buckling layer **128** to release from a flat planar orientation as illustrated by **106** (FIG. 1A) to the curved shape as illustrated by **128** (FIG. 1B). The buckling layer **128** develops a maximum displaced height indicated by **134**. The buckling layer **128** has a horizontal extent indicated by **132**. Note that the horizontal extent **132** can be less than the extent of the region **124**. The relationship between the horizontal extent **132** and the region **124** depends on the thickness of the buckling layer, the material properties, the magnitude of the compressive stress, and the dimensions and geometry of the projected shape of a buckling layer. In one non-limiting example, a horizontal extent **132** (850 μm) was 85% of the length of the region **124** (1000 μm). A top view **140** of the buckling layer **128** is illustrated in **140** (FIG. 1C) for a variety of projected shapes.

FIG. 1C illustrates, generally at **140**, various projected areas of buckling layers within a microstructure, according to embodiments of the invention. With reference to FIG. 1C, a released buckled shape can have any type of projected area. The shape of the projected area depends on the patterning that was employed in order to release a buckling layer over an area. A rectangular shape is indicated at **142**, a round shape is indicated at **144**, and an oval shape is indicated at **146**. A triangular shape is indicated at **148**, a square shape is indicated at **150**, and a general user defined shape is indicated at **152**.

FIG. 2A illustrates, generally at **200**, a cross-sectional view of a multilayer buckling layer within a microstructure, according to embodiments of the invention. In one embodiment, a silicon-on-insulator (SOI) wafer **202** was patterned to create a matrix of buckled membranes (only one is shown in the figure for clarity). In this example, an N-type silicon substrate **204** has a thickness of 400 micrometer (μm) indicated at **216**. A silicon dioxide layer **206**, having a thickness **208** of 2 μm was thermally grown on a top layer **210** also referred to as a device layer having a thickness **212** of 5 μm and made from the same material as the substrate **204** and

then sandwiched between the substrate **204** and device layer **210**. The bottom of the substrate was patterned over an area **214** and etched to a depth of 400 μm , thereby removing the substrate from beneath the silicon dioxide layer **206**.

Various methods can be used to etch the substrate **204**. For example, a layer of silicon dioxide (not shown for clarity) was deposited on the bottom of the wafer **202** followed by a layer of photo resist (also not shown for clarity). The photo resist was then lithographically patterned and developed using standard micromachining techniques. A Buffered Oxide Etch was then used to etch through the silicon dioxide layer and then Deep Reactive Ion Etching (DRIE) was used to remove silicon selectively from beneath the silicon dioxide layer **206**. Other techniques can be used such as an anisotropic wet etch using Tetramethylammonium Hydroxide (TMAH). Other micromachining techniques can be used; embodiments of the invention are not limited by the choice of micromachining techniques.

After removal of the substrate **204**, over the area **214**, the silicon dioxide/device layer **206/210** releases to form a buckling layer **205** with two sub-layers. This is the first of two stable states for the buckling layer. The other or second stable state is referred to as a "popped through" position and is as illustrated below in FIG. 2D. In this example, the resulting buckled membrane **205** had a projected area which was square in shape with dimensions of 1 millimeter (mm) on edge. A resulting maximum deflected height **218** is approximately 15 μm .

FIG. 2B illustrates, generally at **220**, contacting a buckled microstructure membrane with a pseudo point load, according to embodiments of the invention. Referring to FIG. 2B, a calibrated micro Newton (μN) force sensor **222** is used to apply a pseudo point load to the buckled membrane **205** over a contact area **226**. In the experiment resulting in the measurement shown below in FIG. 2C, a force sensor from FemtoTools model FT-S270 was used. This force sensor, mounted to a piezoelectric actuator with a translation range of 20 μm , is capable of applying loads in the micro Newton range (μN). Force sensor **222** has an actuator **224**. The actuator **224** has a contact pad **228** which applies the load to the buckled membrane **205** over the contact area **226**. The contact area **226** is the portion of the buckled membrane **205** that is directly under the contact pad **228**. The contact area **226** is much smaller than the surface area of the buckled membrane **205**. The dimensions of the contact pad are 50 μm by 50 μm . It is important to note that the force sensor **222** and the actuator **224** are used to apply a controlled displacement (along with a corresponding application of force) to the buckled membrane **205**. The controlled displacement is used to determine a load the buckled membrane applies in response to the controlled displacement. The methods described above provide an ability to characterize the physical behavior of a MEMS structure or a MOEMS structure which is superior to exposing the entire surface of such structures to a uniform load through for example pressure exerted by a fluid or a gas.

During the measurement procedure that resulted in the measurement presented in FIG. 2C, the force sensor actuator **224** (FIG. 2B) applies a load to the buckled membrane **205**, which causes the buckled membrane **205** to translate in the direction indicated by an arrow **231**. One such subsequent position associated with the translation of the actuator **224** and the buckled membrane **205** is illustrated by the dashed lines indicating the displaced position of the actuator and membrane and a point **230**. The point **230** shows the location of the actuator tip-buckled membrane interface at one point during the measurement procedure. Following the procedure of applying an increasing displacement to the buckled mem-

brane **205** the measured force verses displacement curve reveals a multi-zoned spring as illustrated in FIG. 2C. This multi-zoned spring has a force-displacement characteristic which corresponds to a stiffness profile which is initially positive, transitions through zero and then becomes negative. Further application of force results in a large deflection of the buckled membrane to a second stable state with curvature that is opposite that of the first stable state. The second stable state is illustrated below in conjunction with FIG. 2D.

FIG. 2C illustrates, generally at **240**, a force-displacement characteristic for the multi-zone microstructure spring of FIG. 2A and FIG. 2B, and a corresponding stiffness-displacement relationship, generally at **260**, according to embodiments of the invention. With reference to FIGS. 2C and **240**, force is plotted on the vertical axis **242** in micro Newtons (μN) and displacement is plotted on the horizontal axis **244** in nanometers. A corresponding stiffness-displacement relationship is plotted in **260** with stiffness plotted on the vertical axis **262** with units of kiloNewtons/meter and displacement plotted on the horizontal axis **264** with units of nanometers. The force-displacement characteristic **240** reveals a multi-zone microstructure spring, characterized by three zones.

A first zone, indicated by **248** and **268**, the positive stiffness zone, is characterized by increasing force with increasing displacement of the buckled membrane. A second zone, indicated by **246** and **266**, the zero stiffness zone, is characterized by a constant force-displacement condition. A third zone **250** and **270**, the negative stiffness zone, is characterized by decreasing force with increasing displacement. As used in this description of embodiments, the term "zone" can imply a point or a region. The extent or lack of extent of a "zone" is determined by the particular physical structure. As such, in some cases, the zero stiffness zone will exist as a point. No limitation is implied by the use of the term "zone" to characterize the physics of the multi-zone microstructure spring.

When the buckled membrane passes a displacement illustrated at **254**, the buckled membrane quickly translates away from the force sensor actuator **224** to assume its second stable state as shown at **262** in FIG. 2D.

FIG. 3A illustrates, generally at **300**, a cross-sectional view of a buckled multi-layered membrane within a microstructure, according to embodiments of the invention. Similar to the microstructure of FIG. 2A, in one embodiment, a silicon-on-insulator (SOI) wafer **302** was patterned to create a matrix of buckled membranes. In this example, an N-type silicon substrate **304** has a thickness of 400 micrometer (μm) indicated at **320**. A silicon dioxide layer **306**, having a thickness **308** of 2 μm was thermally grown and sandwiched between the substrate **304** and a layer **310**. The layer **310** has a thickness **312** of 5 μm and is made from the same material as the substrate **204**. Next a 500 angstrom thick titanium layer **324** was evaporated to the silicon layer **310**. A 3000 angstrom thick gold layer was evaporated on top of the titanium layer. The bottom of the substrate was patterned over an area **318** and etched to a depth of 400 μm ; thereby removing the substrate from beneath the silicon dioxide layer **306**.

Similar to the etching applied to the microstructure of FIG. 2A, various methods can be used to etch the substrate **304**, prior to release of a buckling layer **326**. For example, a layer of silicon dioxide (not shown for clarity) was deposited on the bottom of the wafer **302** followed by a layer of photo resist (also not shown for clarity). The photo resist was then lithographically patterned and developed using standard micromachining techniques. A Buffered Oxide etch was then used to etch through the silicon dioxide layer and then Deep Reactive Ion Etching (DRIE) was used to remove silicon selectively from beneath the silicon dioxide layer **306**. Other tech-

niques can be used such as an anisotropic wet etch using Tetramethylammonium Hydroxide (TMAH). Other micro-machining techniques can be used as well; embodiments of the invention are not limited by the choice of micromachining techniques.

After removal of the substrate **304**, over the area **318**, the buckling layer **326** (which includes layers **306**, **310**, **324**, and **314**) releases to form a buckling layer **326** having four sub-layers. In this example, the resulting buckled membrane **326** has a projected area which was square in shape with dimensions of 1 millimeter (mm) on edge, with a predominantly circular curved shape buckling out of the horizontal plane of the substrate. A resulting maximum deflected height **322** is approximately 10 μm .

During the measurement procedure that resulted in FIG. **3B**, the force sensor actuator **224** (shown in FIG. **2B** but not shown in FIG. **3A** for clarity) applies a load to the buckled membrane **326** (FIG. **3A**) which causes the membrane to translate in the direction indicated by an arrow **327** (FIG. **3A**). As described above in conjunction with FIG. **2B**, the procedure results in force and displacement being recorded as the buckled membrane is translated by application of the pseudo point load applied by the force transducer actuator. Subsequent positions associated with the translation of the buckled membrane and the force transducer actuator are not shown for clarity. The procedure applied to the buckled membrane **326** reveals a multi-zoned spring as illustrated in FIG. **3B**. This multi-zoned spring has a force-displacement characteristic which corresponds to a stiffness profile which is initially positive, transitions to zero and then becomes negative. Further application of force results in a large deflection of the buckled membrane to a second stable state with curvature that is opposite that of the first stable state.

FIG. **3B** illustrates, generally at **330**, a force-displacement characteristic for the multi-zone microstructure spring of FIG. **3A**, and a corresponding stiffness-displacement relationship, generally at **360**, according to embodiments of the invention. With reference to FIG. **3B** at **330**, force is plotted on the vertical axis **332** with units of micro Newtons (μN) and displacement is plotted on the horizontal axis **334** with units of nanometers. A corresponding stiffness-displacement relationship is plotted in **360** with stiffness plotted on the vertical axis **362** with units of kiloNewtons/meter and displacement plotted on the horizontal axis **364** with units of nanometers. The force-displacement characteristic **330** reveals a multi-zone microstructure spring characterized by three zones.

A first zone indicated by **338** and **368**, the positive stiffness zone, is marked by increasing force with increasing displacement of the buckled membrane. A second zone indicated by **336** and **366**, the zero stiffness zone, is characterized by a constant force-displacement condition. A third zone **340** and **370**, the negative stiffness zone, is characterized by decreasing force with increasing displacement. The zero stiffness zone **336/366** can be a point or a region. No limitation is implied by the use of the term "zone" to characterize the physics of the microstructure spring.

When the displacement of the buckled membrane approaches the end of the negative stiffness zone, as indicated by **344**, the buckled membrane quickly translates away from the force sensor actuator **224** to assume its second stable state which is qualitatively shown at **262** in FIG. **2D**.

The addition of the metal layers, i.e., 500 angstroms of titanium **324** and 3000 angstroms of gold **314** has increased the linearity of both the positive stiffness zone and the negative stiffness zone as illustrated by the measurements presented in FIG. **3B**. In various embodiments, a substantially linearized negative stiffness spring is obtained from a buckled

membrane within a microstructure. Such devices have three zones for operation, which are selectable based on an initial displacement from a rest position of the buckled membrane.

FIG. **4** illustrates, generally at **400**, a cross-sectional view of a buckled layer (buckled membrane) within a microstructure, according to additional embodiments of the invention. With reference to FIG. **4**, buckling of a layer can be obtained by localized ion implantation into the layer. Ions implanted during ion implantation induce a compressive stress in the buckling layer. The compressive stress induces buckling, which results in a release of a buckling layer into a curved shape that functions as a multi-zoned microstructure spring. The magnitude of the compressive stress induced in the layer depends on the dose selected and the types of ions used. Heat treatment can be applied at approximately 200 degrees C. to trigger release of the buckling layer **406** shows the buckling layer after release into a curved shape. Note that the buckling layer **406** and the substrate **404** can be the same material; different coefficients of thermal expansion within layers is not required in order to release a buckling layer via ion implantation. Thus, in the example of FIG. **4** both the substrate and the buckling layer can be made from silicon.

Ion implantation can also be used to release a buckling layer when the buckling layer has a coefficient of thermal expansion that is larger than the coefficient of thermal expansion of the substrate. Formation of a layer with a coefficient of thermal expansion which was larger than the coefficient of thermal expansion of the substrate would not result in release of the buckling layer since the buckling layer would be in a state of tension. Ion implantation is used to overcome the state of tension and to create a state of compression, which will result in release of the buckling layer.

Note that the state of tension or compression within a buckling layer of a microstructure depends on, in general: the coefficients of thermal expansion of the materials (e.g., individual; layers of the microstructure), the formation temperature of the microstructure, and the operating temperature of the microstructure. For example, a buckling layer that is in a state of tension at 20 degrees Centigrade will buckle at a temperature above 20 degrees Centigrade (e.g., 200 degrees Centigrade) since the buckling layer will expand more than the substrate (assuming a coefficient of thermal expansion of the buckling layer is larger than a coefficient of thermal expansion of the substrate). Therefore, materials, coefficients of thermal expansion, operating temperatures, and process steps, e.g., ion implantation are considered when buckling is desired within a microstructure.

Many variations in microstructures can exist and many different materials can be used for the substrate and buckling layers. Therefore, depending on the material used for the substrate and the material used for the desired buckling layer, the species to be implanted via ion implantation will be selected to achieve appropriate compressive stress within the material's lattice structure.

An example of a buckling layer having a coefficient of thermal expansion that is greater than the coefficient of thermal expansion of a substrate is a buckling layer made from silicon nitride Si_3N_4 , having a coefficient of thermal expansion of $3.4 \times 10^{-6} \text{ mm/K}$ which can be released from a substrate of silicon having a coefficient of thermal expansion of $2.6 \times 10^{-6} \text{ mm/K}$ via ion implantation. Similarly, a buckling layer can be made from alumina Al_2O_3 and can be released from a silicon substrate.

FIG. **5** illustrates, generally at **500**, a cross-sectional view of a buckled layer within a microstructure, according to additional embodiments of the invention. Referring to FIG. **5**, a buckling layer **506** is illustrated that has reduced adhesion to

a substrate **504** over a region **508**. Outside of the region **508**, the buckling layer **506** has adhesion sufficient to overcome any differential compressive stress residing within the buckling layer. Adhesion between the buckling layer **506** and **504** over the area **508** is too low to prevent buckling.

Referring to **550** in FIG. **5**, release of a buckling layer can be accomplished by application of a first layer that has limited adhesion with the substrate **504**, such as a layer **552**. In various embodiments, the layer **552** is made from an organic material which provides less adhesion than the adhesion obtained between the buckling layer **506** and the substrate **504**. In various embodiments, the layer **552** can be made from polyethylene terephthalate, parylene, benzocyclobutene, etc. For example, a sub-layer of parylene can be deposited by gas spraying on the substrate, patterned by a photolithography step to limit application to the area where release is desired, i.e., **508**. Subsequent application of the buckling layer **506** results in limited adhesion under the area **508**. Release of the buckling layer can be accomplished by any of the methods previously described, resulting in the buckled membrane **506**.

Adhesion between a buckling layer **506** and the substrate **504** can be decreased by a process step(s) in the manufacture of the microstructure for example by an application or a deposition of an intermediate layer (not shown in FIG. **5** at **500**), such as by application of liquids e.g., a photosensitive resin such as Unity 2203P from Promerus, LLC.

Depending on the substrate and intended use of the microstructure, buckling can be induced during deposition of a second sub-layer on top of a first sub-layer where the second sub-layer has a high coefficient of thermal expansion than the coefficient of thermal expansion of the first sub-layer. A vacuum heat treatment at **300** degrees C. for several minutes can facilitate release of the buckling layer.

Alternatively, for a liquid sub-layer of propylene carbonate or water, degradation of adhesion can occur from evaporation at temperatures around **100** degrees C., resulting in release of the buckling layer.

FIGS. **1A-5** above and the discussion directed to them describe various methods of creating a buckled membrane on a microstructure. In various embodiments, a reduced stiffness microstructure (RSM) is made from two opposing buckled membranes with tailored properties.

Referring to FIGS. **6A**, **6B**, and **6C**, FIG. **6A** illustrates a force-displacement characteristic of a buckled membrane, according to embodiments of the invention. A first buckled membrane is shown generally at **600** in FIG. **6A**. A first buckled membrane **602** has a buckling direction indicated at **603**; the first buckled membrane **602** is part of a first buckling layer **605**. The first buckled membrane **602** is loaded at **604**, which causes the membrane to deflect opposite to the buckling direction **603**. A force-displacement plot is shown at **606** with force plotted on the vertical axis at **608** and displacement along a horizontal axis at **610**. In one embodiment, the force-displacement plot **606** is the measurement shown earlier in FIG. **2C**.

The load **604**, applied to the first buckled membrane **602**, is plotted at **614**, the load **614** produces a displacement **612** as indicated on curve **606**. A point **616** indicates the zero slope of the force-displacement plot **606** which is where the stiffness of the first buckled membrane **602** is zero.

Referring now to **630** in FIG. **6B**, a second buckled membrane **632** is positioned to oppose the first buckled membrane **602**. The second buckled membrane **632** is part of a second buckling layer **635**. The second buckled membrane **632** is designed to have a force-displacement characteristic **636** that is identical to the force-displacement characteristic **606** of the first buckled membrane **602**. As used in this detailed descrip-

tion of embodiments, the term “opposing” refers to the situation where membranes have buckled in the opposite direction. Such a case is illustrated by buckling direction **633** (arrow to the right) which is opposite to the buckling direction **603** (arrow to the left) of the first buckled membrane **602**.

A load **634** displaces the second buckled membrane **632** to the left. A point **646**, on the displacement axis, indicates the zero slope of the force-displacement plot **636** which is where the stiffness of the second buckled membrane **632** is zero.

Referring now to **660** in FIG. **6C**, the first buckled membrane **602** and the second buckled membrane **632** have been brought together into contact with each other, thereby developing a mutual preload, to the point where the point **616** and the point **646** overlap each other, resulting in point **662**. Such a condition is referred to as aligning the force-displacement responses or characteristics of the two opposing membranes. The force **612** and **642** represent equal and opposite forces applied to buckled membrane **602** and **632**, respectively. Loads **612** and **642** are indicated in **660** as coincident with each other.

FIG. **7A** illustrates an operating zone of a reduced stiffness microstructure (RSM), from **660** in FIG. **6C**, according to embodiments of the invention. Referring now to FIGS. **6A**, **6B**, **6C**, and FIG. **7A**, the opposing buckled membranes were selected to provide very similar to identical force-displacement responses. In this case, a zero-stiffness operating zone was desired, the aligned opposing buckled membranes provide a zero-stiffness operating zone indicated at **702**. In the operating zone, a force applied to a membrane surface at **664** or **666**, which is along the buckling directions **668** of the membranes, produces motion of the buckled membrane microstructure.

Asymmetry in the force-displacement characteristics results in a net non-zero force exerted between the membranes along the buckling axis in two zones. These two zones function as potential energy stops which provide restorative forces that help keep the opposing buckled membranes in the operating zone **702**. Two such non-zero force conditions are illustrated in FIG. **7A**.

A first zone where the net force between the membranes is non-zero is indicated at a zone **704**. In the zone **704**, the second buckled membrane **632** exerts a force on the first buckled membrane **602** which is larger than the opposing force exerted by the first buckled membrane **602** (e.g. **706** on the curve **636**), thereby causing the opposing buckled membranes to move to the right for displacement positions in the zone **704**, such as **712**. At displacement **712**, the net non-zero force exerted on the opposing buckled membranes is the difference between the curve **636** and the curve **606**, which is indicated at **710**. The force-displacement characteristics **606** and **636** for the buckled membranes **602** and **632** diverge in the zone **704** resulting in a potential energy stop at a first limit of the translation range **668** (FIG. **6C** in **660**). At displacement **712** the net non-zero force **710** manifests on the opposing buckled membranes as indicated by an arrow **713** which provides a restorative force tending to return the opposing buckled membranes to the operating zone **702**.

A second zone where the net force between the opposing buckled membranes is non-zero is indicated at **708**, which is to the right of the operating zone **702**. In the zone **708**, the first buckled membrane **602** exerts a force on the second buckled membrane **632** which is larger than the opposing force exerted by the second buckled membrane **632** (e.g., **716** on the curve **606**), thereby causing the opposing buckled membranes to move to the left for displacement positions in the zone **708**, such as **714**. At displacement **714**, the net non-zero force exerted on the opposing buckled membranes is the

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difference between the curve **606** and the curve **636**, which is indicated at **720**. The force/displacement characteristics **606** and **636** for the buckled membranes **602** and **632** diverge in the zone **708** resulting in a second potential energy stop at a second limit of the translation range **668** (FIG. 6C in **660**). At displacement **714** the net non-zero force **720** manifests on the opposing buckled membranes as indicated by an arrow **722** which provides a restorative force tending to return the opposing buckled membranes to the operating zone **702**. Thus, a potential energy well is created with two opposing buckled membranes with force-displacement characteristics that have been aligned.

The dynamic response to motion, described directly above, the case where a zero-stiffness zone is created in an RSM can be referred to as a potential energy well. At one end of the translation range, along the buckling directions or axes **668**, a first potential energy stop exists within the zone at **704**. A second potential energy stop exists at the other end of the translation range within the zone **708**. In the zero-stiffness zone **702**, applied force results in kinetic energy or motion and flexing of the buckled membranes along **668**. The motion of the buckled membranes along **668** (in the operating zone **702**) results in a decrease in potential energy of one membrane with a corresponding simultaneous increase in potential energy of the other membrane while the contact area of the membranes translates along the buckling directions or axes **668**. Outside of the operating zone **702**, the potential energy of one buckled membrane is larger than the potential energy of the other buckle membrane. This condition results in a potential energy stop as previously described.

The alignment illustrated in FIG. 7A illustrates a method to achieve a zero-stiffness elastic micro-mechanical structure (RSM). Variations from zero are obtained in different ways, according to different embodiments. In one method, the membranes do not have identical force-displacement characteristics. This is accomplished by making one membrane stiffer than the other. Membrane stiffness is related to membrane thickness, as well as to membrane composition, such as membrane area, materials, etc. Therefore, in order to create membranes with different force-displacement characteristics, the membranes are intentionally made to be non-identical to each other. One example of non-identical force-displacement characteristics is illustrated in FIG. 7B.

FIG. 7B illustrates, generally at **750**, another operating zone of a reduced stiffness microstructure, according to embodiments of the invention. With reference to FIG. 7B, a single operating zone is illustrated for a RSM. A force-displacement curve **756** results from a first buckled membrane. A second buckled membrane has a force-displacement curve represented by **758**. Force is plotted on an axis **752** and displacement of the contact area is plotted on an axis **753**. Both buckled membranes are in contact with each other and a state of preload exists between the two buckled membranes, which causes the membranes' force-displacement characteristics **756** and **758** to become aligned. However, in the present case, there is always a non-zero force existing between the buckled membranes. The magnitude of the force is represented by the difference between force-displacement characteristics **756** and **758**. For example, at a displacement indicated at **754** the non-zero force is indicated at **760**. Note that the magnitude of **760** is smaller than either **762** or **764**. Thus, a reduced stiffness microstructure results from the two opposing buckled membranes with non-identical mechanical properties.

FIG. 8 illustrates, generally at **800**, locating two substrates, according to embodiments of the invention. With reference to FIG. 8, in one embodiment, the opposing buckled membranes

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previously discussed are constructed on separate substrates and then the substrates are located via micromanipulation before joining the substrates together. Buckled membranes can be released from their respective substrates either before joining the substrates together or after the substrates are joined together via the methods previously described or by methods as of yet unknown. Embodiments of the invention are not limited by the way in which a buckled membrane is released from the substrate.

In one embodiment, a first multilayered microstructure **802** has a substrate indicated at **804** and a multi-layered buckling layer indicated by layers **822** and **806**. In one embodiment, **822** is a layer of silicon dioxide, **806** is a layer of mono-silicon, and **804** is mono-silicon. A second multilayered microstructure **808** has a substrate indicated at **810** and a multilayered buckling layer **820** and **812**. In one embodiment, **810** is a mono-silicon layer, **820** is a layer of silicon dioxide, and **812** is a layer of mono-silicon. In one embodiment, spacers **814** and **816** are made from poly-silicon and are deposited on **812**. A thickness **818** of the spacers is selected to provide the proper initial displacement of the buckled membranes following release of the membranes from their substrates. In the examples given in conjunction with FIGS. 6A, 6B, 6C, and FIG. 7A, the desired initial displacement of the opposing buckled membranes is indicated as **616** and **646** (**616** is equal to **646** in the example of FIGS. 6A and 6B). Therefore, the thickness **818** of the spacer **814** and **816** is two times the displacement **616**. Alternatively, the thickness of the spacers **816/814** can be selected to provide a different force-displacement characteristic for the opposing coupled buckled membranes according to the teaching presented herein.

To provide the correct distance between buckled membranes, the spacers **816** and **814** can be chemically mechanically polished to planarize the deposited surface. Alternatively, optional spacers **832** and **834** can be deposited onto the layer **806**. In such a case, the thickness **818** of the spacer **816** and **814** combined with the thickness **836**, of the spacers **832** and **834**, to equal two times the displacement **616** (which is also equivalent to the displacement **646** or **662**). For example, the thickness **818=836=616**. Alternatively, when two spacers are used, the desired separation between the top surfaces of the opposing buckling layers can be apportioned between the two spacers by any fractional distribution.

The substrate **808** and the substrate **802** are located relative to one another by micromanipulation, indicated by arrows **826** and **830** and then the substrates are brought into contact with one another as indicated with arrows **824** and **828**. The substrates are joined together by various means such as direct bonding, Plasma Activated bonding, Eutectic bonding, etc. Those of skill in the art will recognize other bonding methods that are suitable for this use. The bonding methods listed herein are given by way of example and do not limit embodiments of the invention.

FIG. 9 illustrates, generally at **900**, bonding two substrates together, according to embodiments of the invention. With reference to FIG. 9, the two substrates described in FIG. 8 are shown bonded together in **900**. Note that in FIG. 9, the membranes have not yet been released from the substrates. Following bonding of the substrates, buckled membranes are released from the substrate **808** and **802**. In one embodiment, the outer surface of **808** and **802** are patterned and etched to remove substrate **804** and **810** from the region between the spacers. The resulting microstructure is shown in FIG. 10.

FIG. 10 illustrates the state of the buckled membranes after the membranes have been release from the substrates. Alternatively, in some embodiments, the membranes are released before the substrates are joined together. In such a case the

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membranes are released before the substrates are joined together and care is taken to align buckled membranes from one substrate with buckled membranes from the other substrate. Membranes are released following any of the methods known to those of skill in the art. The example given above is for the purpose of illustration and does not limit embodiments of the invention in any way.

FIG. 10, illustrates, generally at **1000**, a pair of coupled buckled membranes, according to embodiments of the invention. With reference to FIG. 10, a multi-layered microstructure **1002** has a substrate **1004** and a first multi-layered buckling layer, which includes a sub-layer **1022** and a sub-layer **1006**. A first buckled membrane **1028** has been released by removal of the substrate **1024** over an area **1023**.

A multi-layered microstructure **1008** has a substrate **1010** and a second multi-layered buckling layer, which includes a sub-layer **1012** and a sub-layer **1020**. A second buckled membrane **1026** has been released by removal of the substrate **1022** over an area **1023**. Removal of substrate **1024** and **1022** cause the first buckled membrane **1028** to contact the second buckled membrane **1026** over a contact area **1030**.

A thickness **1034** of spacers **1014** and **1016** has been designed to provide the desired force-displacement characteristic for the reduced stiffness microstructure (RSM). Spacers **1014** and **1016** can be sized to provide an open area (void) between the buckled membranes that is not the same size as the area indicated at **1023**. Such variation is indicated by dashed lines **1031** and **1032**.

In one or more embodiments, the RSM of FIG. 10 has been designed according to the descriptions presented in support of the previous figures to produce a zero-stiffness RSM or a reduced stiffness RSM.

FIG. 11 illustrates, generally at **1100**, a mass (or spacer) located between a pair of coupled buckled membranes, according to embodiments of the invention. With reference to FIG. 11, a mass **1106** is deposited on one of the buckling layers (**1028** or **1026**) before the substrates are aligned and bonded together, such as in the state of assembly shown in FIG. 8. The thickness of the spacers **1102** and **1104** is sized to accommodate the added thickness of the mass **1106**, consistent with the desired elastic response of the RSM. For example, if a mass **1106** were added to the RSM of FIG. 10, an added thickness **1108** is added to the thickness **1034** of the spacers **1014** and **1016** in order to preserve the elastic response of the RSM.

The potential energy well described above in conjunction with a RSM that has a zero-stiffness zone provides potential energy boundaries which serve to limit the displacement of a pair of opposing coupled buckled membranes. If excitation energy is sufficiently high, the pair of coupled buckled membranes can travel outside of the potential energy well boundaries and "pop through" to one side or the other. Popping through can be prevented with mechanical stops. FIG. 12 illustrates mechanical stops used with a pair of coupled buckled membranes, according to embodiments of the invention.

With reference to FIG. 12A, a RSM is shown at **1201**. In one embodiment, **1201** is the RSM **1000** from FIG. 10. An upper layer **1202** has been micro machined to produce a stop **1204** which has a height or thickness **1205**. A lower layer **1206** has been micro machined to produce a stop **1208**, which has a height **1205**.

In FIG. 12B at **1250** the upper layer **1202** and the lower layer **1206** have been bonded to the RSM **1201**. The upper layer **1202** and the lower layer **1206** are positioned through micromanipulation to place the stops at a desired location. Desired locations can be any position behind the buckled membrane. For example, the stop **1204** or stops **1204/1208**

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can be centered on the buckled membrane's area, off to one side, etc. The stop can be arrayed as a single stop (as shown in FIG. 12A and FIG. 12B) or the stop **1204** can be a plurality of stops.

The stops **1204** and **1208** limit the travel of the coupled buckled membranes to the distance shown at **1258** and **1260**. A measurement of the force-displacement characteristic of a buckled membrane will provide the information needed to determine the distance represented by **1258** and **1260**. Referring to FIG. 7A, one design point can be to set **1258** equal to one half of the width of the operating zone **702**. Another design point can be wider, which can include a portion of zone **704** and **708**, keeping in mind the desire to prevent pop through. Alternatively, the stops can be located to allow pop through.

RSM devices incorporating coupled buckled membranes can be made from a single substrate in order to avoid micro-manipulation of separate substrates. A pair of opposing buckled membranes needs a cavity into which the membranes buckle into and then contact each other following release. Such cavities can be created by etching into a multilayered microstructure, such as one made from a series of layers of silicon on insulator (SOI). Following creation of a cavity, membranes can be released by etching each respective surface or by ion bombardment on the respective surfaces.

Embodiments of the RSM structure presented above can be utilized in a host of MEMS or MOEMS devices. One such device is a capacitive MEMS switch. A RSM used in a capacitive MEMS switch requires very low maintaining voltage because of the very low (including zero) stiffness provided by the RSM. In one embodiment, such a switch is opened through electrostatic repulsion and kept closed through stiction, thereby requiring very low to no maintaining voltage.

In an ohmic MEMS switch the coupled buckled membrane of a RSM device can be utilized as either the contact mounting surface or the structure that comes into contact with a stationary contact. In one embodiment, the mechanical stops described in above in FIG. 12 can be used as contacts of a switch. In one embodiment, the distances **1208** and **1210** are set to allow the coupled buckled membrane to pop through, thereby creating a state for the switch in a "popped through" position for the coupled buckled membrane. The degree of restoring force and actuation force is determined by alignment of the force-displacement characteristics of the membranes and by the design of the buckled membranes.

RSM devices have application in a host of MEMS and MOEMS devices as described above. A non-limiting list of such devices include: stress relief, passive energy damping, pressure control, support structure, entropy reduction devices, energy transfer devices, energy harvesting devices, pressure sensors, etc.

For purposes of discussing and understanding the embodiments of the invention, it is to be understood that various terms are used by those knowledgeable in the art to describe techniques and approaches. Furthermore, in the description, for purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the present invention. It will be evident, however, to one of ordinary skill in the art that the present invention may be practiced without these specific details. In some instances, well-known structures and devices are shown in block diagram form, rather than in detail, in order to avoid obscuring the present invention. These embodiments are described in sufficient detail to enable those of ordinary skill in the art to practice the invention, and it is to be understood that other embodiments

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may be utilized and that logical, mechanical, electrical, and other changes may be made without departing from the scope of the present invention.

As used in this description, “one embodiment” or “an embodiment” or similar phrases means that the feature(s) being described are included in at least one embodiment of the invention. References to “one embodiment” in this description do not necessarily refer to the same embodiment; however, neither are such embodiments mutually exclusive. Nor does “one embodiment” imply that there is but a single embodiment of the invention. For example, a feature, structure, act, etc. described in “one embodiment” may also be included in other embodiments. Thus, the invention may include a variety of combinations and/or integrations of the embodiments described herein.

While the invention has been described in terms of several embodiments, those of skill in the art will recognize that the invention is not limited to the embodiments described, but can be practiced with modification and alteration within the spirit and scope of the appended claims. The description is thus to be regarded as illustrative instead of limiting.

What is claimed is:

1. A microstructure, comprising:
 - a first substrate;
 - a first buckled membrane, the first buckled membrane is connected to the first substrate, the first buckled membrane has a first curved shape, a first area, and has buckled along a first buckling direction; and
 - a second buckled membrane, the second buckled membrane is connected to a second substrate, the second buckled membrane has a second curved shape, a second area, and has buckled along a second buckling direction, the second buckling direction is opposite to the first buckling direction, wherein the first buckled membrane and the second buckled membrane are in contact over a contact area, the contact area is less than the first area or the second area, the first buckled membrane has a first membrane stiffness when loaded over the contact area and displaced opposite to the first buckling direction, the second buckled membrane has a second membrane stiffness when loaded over the contact area and displaced opposite to the second buckling direction.
2. The microstructure of claim 1, wherein the first area is not equal to the second area.
3. The microstructure of claim 2, wherein a composition of the first buckled membrane and a composition of the second buckled membrane have been selected to provide similar force-displacement responses for each membrane when each membrane is loaded along each membrane’s buckling direction.
4. The microstructure of claim 1, further comprising:
 - a first connection link, the first connection link is in contact with the contact area, translation of the connection link moves the contact area along a translation axis, the translation axis is parallel to the buckling directions.
5. The microstructure of claim 1, further comprising:
 - a first potential energy stop, the first potential energy stop is formed when the contact area has translated along the first buckling direction and its motion is impeded by a fixed amount;

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- a second potential energy stop, the second potential energy stop is formed when the contact area has translated along the second buckling direction and its motion is impeded by a fixed amount; and
 - a potential energy well, the potential energy well exists between the first potential energy stop and the second potential energy stop.
6. The microstructure of claim 5, wherein the first potential energy stop occurs when the first membrane stiffness and the second membrane stiffness diverge.
 7. The microstructure of claim 5, wherein contact area motion is impeded by a physical stop.
 8. The microstructure of claim 1, wherein the first substrate and the second substrate are the same substrate.
 9. A microstructure spring, comprising:
 - a substrate; and
 - two opposing buckled membranes, further comprising:
 - a first buckled membrane, the first buckled membrane is part of a first buckling layer and the first buckling layer is connected to the substrate;
 - a second buckled membrane, the second buckled membrane is part of a second buckling layer, the second buckling layer is connected to the substrate, and the two opposing buckled membranes buckled in opposite directions such that the opposing buckled membranes are in contact over a contact area and the contact area is less than the total area of either buckled membrane, and the contact area can translate along an axis that is substantially perpendicular to a plane of the substrate.
 10. The microstructure spring of claim 9, wherein the axis is along the buckling directions.
 11. The microstructure spring of claim 9, wherein the two opposing buckled membranes are substantially similar.
 12. The microstructure spring of claim 9, wherein a range of translation of the contact area comprises:
 - a first stop at a first limit of translation along the axis;
 - a second stop at a second limit of translation along the axis; and
 - a translation region, the translation region is bounded by the first stop at one end and the second stop at the other end, in the translation region a stiffness of the microstructure spring along the axis is less than the absolute value of a stiffness of either of the two opposing buckled membranes.
 13. The microstructure spring of claim 9, wherein an area of one of the two opposing buckled membranes is different from an area of the other of the two opposing buckled membranes.
 14. The microstructure spring of claim 9, wherein translation of the contact area is limited by a physical stop.
 15. The microstructure of claim 9, wherein a potential energy stop occurs when the force-displacement characteristics of the membranes diverge.
 16. The microstructure spring of claim 9, wherein a spacer is between a first buckling layer and a second buckling layer.
 17. The microstructure spring of claim 9, wherein a mass is between a first buckled membrane and a second buckled membrane.

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